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Ammonia and methane emissions from small herd cattle buildings in a cold climate

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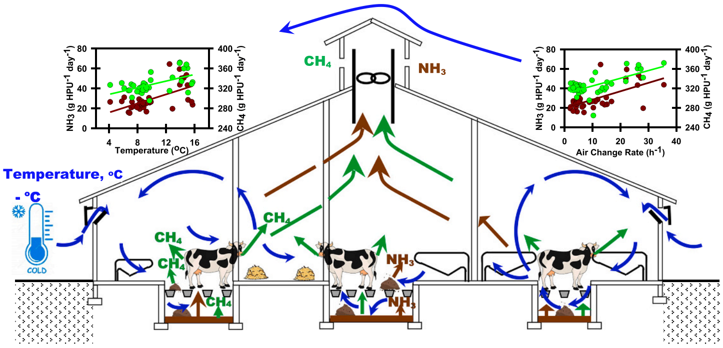
HIGHLIGHTS

- Indoor climate, NH_3 and CH_4 emissions were measured in small-herd cattle barns.
- The barns differed, with three mechanically and one naturally ventilated.
- On HPU basis, lower stocking barns emitted 48 % more NH_3 than higher stocking herds.
- Similarly, beef barn emitted 6–43 % more NH_3 and 25–79 % less CH_4 than the dairy barns.
- Relative humidity and NH_3 emissions showed a positive relationship.

GRAPHICAL ABSTRACT



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ABSTRACT

Ammonia (NH_3) and methane (CH_4) emission measurements that reflect local production conditions are required to track progress in national emission policies and verify emission factors. The findings can also be used to better understand key factors influencing emissions. This is especially important in Norway, which has long cold winters, and small cattle herds in mechanically ventilated buildings. However, until now, NH_3 and CH_4 emissions from Norwegian cattle buildings have not been reported in literature. Moreover, in other cold climates, NH_3 and CH_4 emissions are often taken from large dairy herds in naturally ventilated buildings, with less focus on suckler cows. The objectives were to assess indoor climate, report NH_3 and CH_4 emissions and examine the impact of climatic factors on NH_3 and CH_4 emissions in three small herd dairy and suckler cow buildings over three seasons. Three of the buildings had mechanical ventilation, while one was naturally ventilated. The suckler building had higher relative humidity (RH > 90 %) and NH_3 concentrations (> 25 ppm) due to lower minimum air change rate (ACH = 1.2 h^{-1}). The suckler building also had the highest NH_3 emissions (2.04 g Livestock Unit $(LU)^{-1}$ h^{-1}) followed by the mechanically ventilated dairy building (1.92 g LU^{-1} h^{-1}) with the highest ACH. These two buildings had the lowest stocking densities and floor areas. In contrast, the suckler building had the lowest CH_4 emissions (6.8–10.7 g LU^{-1} h^{-1}). Methane emissions from the dairy building with the supply-exhaust air mixing system (16.4–19.3 g LU^{-1} h^{-1}) was higher than the other dairy buildings (11.7–13.8 g LU^{-1} h^{-1}). Temperature influenced NH_3 emissions however, the direction of association between temperature and NH_3

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emissions differed among buildings. Relationship between RH and NH_3 emissions was positive, but the correlation coefficient ($R^2 = 0.67$) was strongest in the building with the highest RH.

1. Introduction

Intensive cattle rearing emits a wide range of pollutants into the atmosphere (Kammer et al., 2020; Yuan et al., 2017), however the hottest topic today is ammonia (NH_3) and methane (CH_4) emissions (Steinfeld et al., 2006). Ammonia emissions from cattle production are important because they endanger ecosystems and biodiversity through acidification and eutrophication, and they are a precursor to the formation of secondary particulate matter in the atmosphere, which endangers public health (Behera et al., 2013). In contrast, emitted CH_4 is a potent greenhouse gas (GHG) with 28 times the global warming potential of CO_2 (Pachauri et al., 2014). In cattle buildings, the sources of NH_3 and CH_4 differ, but factors influencing their production can be divided into three categories: animal feed, manure management, and indoor climatic conditions.

Ammonia is produced when urinary urea from cattle mixes with faeces, followed by the microbiological breakdown of urea into NH_3 and CO_2. Temperature, air velocity, and relative humidity (RH) are important indoor climatic factors that influence NH_3 emissions from cattle buildings (Qu et al., 2021; Saha et al., 2014; Sanchis et al., 2019; Schrade et al., 2012). Methane production from manure, like enteric CH_4, is dependent on methanogens. However, manure temperature, along with manure retention time, volatile solids content, and the extent of anaerobic conditions in stored manure, are regarded as key factors influencing manure CH_4 production (IPCC, 2019; Sommer et al., 2007). Given that enteric CH_4 production is primarily influenced by feed type, amount consumed, and animal production, there are conflicting reports on the impact of indoor climatic factors on enteric CH_4 production (Hempel et al., 2016; Jungbluth et al., 2001; Rong et al., 2014; Saha et al., 2014). Despite this, some studies suggest that indoor temperature and RH have an indirect effect on enteric CH_4 production due to their effects on cow thermoregulation and metabolism, as well as activity and feed intake (Hempel et al., 2016; Huang and Guo, 2018; Ngwabie et al., 2011; Saha et al., 2014).

In Norway, cattle production is the largest contributor of both NH_3 and CH_4 emissions because: (1) Manure management is the leading source of atmospheric NH_3 emissions (Norway National Inventory Report, 2022). (2) GHG emissions from livestock manure account for 11 % of total agricultural emissions, with cattle manure contributing the most emissions (Carbon Limits, 2020a). And, (3) Enteric CH_4 emissions from dairy and non-dairy cattle account for the greater part of total enteric CH_4 emissions from the livestock sector (Norway National Inventory Report, 2022). Given the importance of NH_3 and CH_4 emissions, Norway is a signatory to the United Nations Framework Convention on Climate Change (Norway National Inventory Report, 2022) and the Gothenburg Protocol (Carbon Limits, 2018). These agreements require Norway to develop, update, and submit annual inventory reports. However, until now, NH_3 and CH_4 emissions from Norwegian cattle buildings have not been reported in literature. As a result, models used to estimate emissions in the National Inventory Report are largely based on international default values and/or expert judgement (Carbon Limits, 2018; Carbon Limits, 2020b; Norway National Inventory Report, 2022), both of which are subject to uncertainty (Ngwabie et al., 2014; Niu et al., 2018; Schrade et al., 2012).

Accurate farm-level emission data reflecting local production and management systems, as well as local climatic conditions, are required to track progress in national emission policies, develop/verify innovative emission abatement techniques, and to enact legislations based on the international agreements (Niu et al., 2018; Schrade et al., 2012). This requirement is even more important given Norway's unique climatic conditions and cattle production systems, which may have a higher impact on NH_3 and CH_4 emissions when compared to other countries. The distinguishing characteristics that may have an influencing effect on NH_3 and CH_4 emissions are as follows: Norway has a wide ambient temperature range across the country (due to its geography) as well as long cold winters. When compared to other cold climate countries, Norway has relatively small dairy and suckler herd sizes (i.e. on average 30 cows) (Statistics Norway, 2023). As a result of the cold climate, mechanical ventilation is more common than naturally ventilated cattle buildings (Næss et al., 2011; Næss and Stokstad, 2011). Furthermore, due to the small herd size, in-house manure storage beneath the slatted floor over a longer length of time is the most common system (Carbon Limits, 2020b; Norway National Inventory Report, 2022). Although all the above factors have been shown to influence NH_3 and CH_4 emissions, field measurements from Norwegian cattle buildings have not been reported in the literature until now. Moreover, in other cold climates, measurements of NH_3 and CH_4 emissions are often taken in large herd dairy buildings with natural ventilation, with less focus on suckler buildings. Thus, in this study, field measurements were taken in three commercial dairy and a suckler cow building with different ventilation design and housing systems over three seasons to:

1. Evaluate diurnal and seasonal variations in indoor climate, air exchange rate (ACH), NH_3 and CH_4 emissions.
2. Report NH_3 and CH_4 emissions compared to other cold climates.
3. Assess environmental factors influencing indoor climate and, NH_3 and CH_4 emissions.

2. Materials and methods

Field measurements were taken in four commercial cattle buildings (Fig. 1). The buildings were in the flatland regions of Central and South-Eastern Norway, at low altitudes of <50 m above sea level. Buildings I, III, and IV were in the Trøndelag Region, while building II was in Oslo. Except for building IV, which was for suckler cows, all the other buildings housed dairy cows. In each building, cows, heifers, and calves were all housed in the same building. The buildings were all loose housing with a resting area (divided into cubicles) and a central feeding alley. The resting area for the cows was elevated above the slatted floor and fitted with rubber mats. Robotic cleaners continuously scraped manure from the slatted floor into the slurry pit in buildings II and III, but only at the dairy cow section. At the calves/heifer section, the manure on the slatted floor was manually scraped at least once a day. The slurry pit beneath the slatted floor in buildings I and II was approximately 3.0 m deep, and 1.2 m and 0.25 m in buildings III and IV, respectively. Buildings III and IV were also equipped with 3.6 m and 3.0 m in-house deep slurry drainage pits at the ends of the slatted floor section, respectively. The accumulated slurry in the pit was emptied during the spring and summer months, except for building III, which was emptied once a month and stored in a separate outdoor storage. Each dairy building had an Automatic Milking Systems (AMS), and the cows had free access to the AMS. Table SM1 in the supplementary material (SM) provides information on the building volume, floor area, and manure management system in the investigated buildings.

The buildings were mechanically ventilated apart from building III, which was naturally ventilated. During the field measurements, the setpoint temperature at the climate controller in all buildings was set between 10 and 13 °C. Gaseous emission measurements were conducted while all the cows were indoors during winter, spring and autumn. There were no measurements in summer because during the day the cows spent more time outdoors than indoors. This was in accordance with Norwegian grazing regulation, which require cows to be on pasture for at least 8 weeks during the summer months. Table SM2 contains details on measurement periods and total measurement hours for each building.

2.1. Buildings

Building I was in Inderøy (63° 53′ 45.24” N and 11° 19′ 19.236″ E). The building was fully insulated and had a flat ceiling, with a ceiling height of 3.0 m measured from the slatted floor. The dairy cow section was equipped with seven mechanically controlled air inlet valves measuring 0.3 m × 0.6 m and positioned opposite each sidewall. However, the glass window openings on the sidewalls of the calve and heifer section of the building (Fig. 1) were manually adjusted by the farmer. There were three exhaust fans in the ceiling: one at the dairy cows' resting/milking area and two at the feeding area.

Building II was in Oslo (59° 54′ 37.476“ N and 10° 40’ 52.248” E). The building had a pitched ceiling and was fully insulated. When measured from the slatted floor, the building had a ridge height of 10.0 m and an eave height of 3.7 m. Three Optimavent systems (J.L. BRUVIK AS, Bergen, Norway) were installed at the ceiling to ventilate the building (Fig. 1). The Optimavent system works on the principle of neutral pressure, with each ventilation duct having a single housing unit that houses both the supply and exhaust fans, allowing the supply air stream to mix with the exhaust air before being delivered into the building. J. L. Bruvik AS (2023) contains a detailed description of how the Optimavent system works.Farm buildings III and IV both had roof pitched ceilings and were at Mære (63° 55′ 43.824″ N and 11° 23′ 36.312″ E). Building III was semi-insulated and had an automatic control natural ventilation system. Measured from slatted floor, it had a ridge height of 7.8 m, eave height of 2.8 m and sidewall height of 1.2 m. The openings in the side walls were 1.4 m high when fully opened, and the ridge opening was 1.0 m wide. The building was situated in an open field with few nearby buildings (Figure SM1). The likely source of gaseous emissions was an open outdoor manure storage tank 180 m away from building III. At this location the predominant wind directions were south-western and north-eastern. Building IV, on the other hand, was a fully insulated mechanically ventilated building. Measured from the slatted floor, it had a ridge height of 5.2 m and eave height of 2.6 m. The building had four exhaust fans at the ceiling with sixteen mechanically controlled sidewall air inlet valves of size 0.3 m × 0.6 m.

2.2. Animals and diet

The dairy cow breed was all Norwegian red (NRF) at all the farms, while the suckler cows were either an NRF-Limousine cross or Hereford. All farms fed their cattle a mixed ration of roughage, concentrate and minerals. Grass silage and barley straw were used as roughage. The concentrate contained milk powder, wheat bran, beet pulp, oats, rapeseed flour, beet molasses, corn, barley, oatmeal flour, soya flour, sugar cane molasses, and other minor ingredients. Table SM3 illustrates the nutritional contents of concentrates for the mature cows at the different buildings. The farms had different feeding schedules. Cows in buildings I and IV were fed twice a day (between 8 a.m. and 9 a.m., and 17 p.m.), while those in building II were fed six times a day (6 a.m., 10 a.m., 14 p.m., 18 p.m., 20 p.m. and 22 p.m.). The farmers delivered feed to the cows in buildings I and IV by trucks, while feeding in building II was automated. Similarly, the robotic feeder in building III fed the dairy cows nine times per day and the other cows twice per day at the following hours: 2 a.m., 8 a.m., 10:30 a.m., 12 p.m., 14 p.m., 17 p.m., 21

Fig. 1. Inside view of the investigated cattle buildings.

p.m. and 23 p.m. In addition to the feed delivered at the feeding alley, the milking cows received concentrate feed at the AMS and the concentrate feeder. Roughage consumption by the cows was not measured during the investigation. However, the concentrate intake at the AMS and concentrate feeder was monitored. The average daily concentrate intake in buildings I, II and III was 9.1 kg, 9.7 kg and 7.9 kg, respectively. Mature cows in building IV received 1 kg of concentrate per day, while young animals aged 8 to 12 months received 3 kg of concentrate per day. The animal mass in buildings I and IV was estimated using a weight tape around the heart girth, whereas those in buildings II and III were estimated using Norwegian cattle production data. Table SM4 shows the production information at the farms.

2.3. Measurements

2.3.1. Climatic and gaseous concentrations

Depending on the building layout, seven to nine HOBO temperature data loggers (Onset Computer Corporation, Massachusetts, USA) were used to measure indoor temperature (Range: −20 to 70 °C; Accuracy: 0.53 °C). Up to six Tinytag data loggers (Gemini Data Loggers Ltd., Chichester, UK) were used to monitor the indoor temperature and relative humidity (RH) (Range: −25 °C to 85 °C with 0 to 95 % RH; Accuracy: 0.6 °C; 3 % RH). During the winter and spring measurements, two Tinytag CO_2 data loggers (Gemini Data Loggers Ltd., Chichester, UK) were used to record CO_2 concentrations (range: 0 to 5000 ppm; accuracy: 0.6 °C; accuracy (50 ppm +3 % of measuring value). One Tinytag CO_2 datalogger was placed in each sidewall opening. Outside climate was monitored using an Oregon scientific weather station (Oregon Scientific, Inc., Oregon, USA): (Range: −40 °C to 65 °C, 0 % to 99 % RH, 0 to 80 m s^{-1}; Accuracy ±0.5 °C, 3 %, and ± 0.9 m s^{-1}, respectively). The data loggers were placed at various locations inside the cattle buildings and registered data at a sampling frequency of 5 min. A thermal camera (FLIR C3, FLIR Systems, Inc., Oregon, USA): (Range: −10 °C to 150 °C; Accuracy ±2 °C or 2 %) was also used to measure surface wall temperatures, and a mini-mist smoke machine was used to assess airflow patterns in the buildings.

A Fourier Transform Infrared Spectrometer (FTIR) gas analyser (GT5000 Terra, Gasmet Technology Oy, Helsinki, Finland) and a multipoint gas stream switcher continuously monitored the gaseous concentrations (CO_2, NH_3, CH_4 and N_2O). The gas analyser's lower detection limit values in pure nitrogen were 0.400 ppm 0.031 ppm, 0.025 ppm, and 0.005 ppm for CO_2, NH_3, CH_4, and N_2O, respectively. The stream switcher system was made up of an 8 Flow-through (SF) selector (Valco Instruments Co. Inc., Texas, USA) and YAGA (YAGA AS, Ski, Norway) stream switcher software. Measurements were taken sequentially at 8 different sample points. At each gas sampling location, air temperature and/or relative humidity were measured in addition to the gas analysis. Before the measurements began, and at least every other second day during the measurements, zero-point calibrations were performed using pure N_2 gas. The Calcmet software (Gasmet Technology Oy, Helsinki, Finland) and YAGA control program sequentially collected at least five gas samples per location to the gas analyser every 30 min.

In the mechanically ventilated buildings, there was at least one gas sample point in the exhaust duct and in the inlet opening. The remaining sample points were located at various heights from the floor at the resting and feeding areas, depending on the building layout. Background gaseous concentrations were monitored at two sampling points in the naturally ventilated building—one in the sidewall opening and the other 10 m away, outside the opposite sidewall. The remaining six sample points were also located at different heights from the floor in the resting and feeding areas. The detailed gas sample points and other sensor locations in the four cattle buildings are shown in Figure SM2. Polytetrafluoroethylene tubes were used to collect gas samples for the FTIR gas analyser, with one minute flushing and two minutes sampling time. As a result, every 30 min, a gas sample was collected and analysed from each sample location. During the data analysis, the last gas samples that were analysed during each sampling episode in an hour were chosen, and the average was computed as the gaseous concentrations at the sample location.

2.3.2. Ventilation and emissions

Ventilation rate, VR ($m^3\ h^{-1}$) was calculated on hourly basis using the CO_2 mass balance (CIGR, 2002) in Eq. (1). Where $CO_{2,in}$ and $CO_{2,out}$ are the indoor and outdoor CO_2 concentration (g m^{-3}), while P_{CO_2} and A are the CO_2 production and relative animal activity (dimensionless), respectively.

$$VR = \frac{10^6 \times P_{CO_2} \times A \times Q_{tot}}{\left(CO_{2,in} - CO_{2,out}\right)} \tag{1}$$

P_{CO_2} was calculated as 0.2 $m^3\ h^{-1}$ per heat production unit (HPU), if the manure pit contributed 10 % to the total CO_2 production (Pedersen et al., 2008). The relative animal activity was computed using the sinusoidal equation in CIGR (2002). The heat production equations in CIGR (2002) were also used to calculate heat production for each animal category, as heat production is influenced by cow category, milk yield, physiological status, and other factors. The total heat production (Q_{tot}) in each building was later converted from W to HPU, where 1000 W = 1 HPU at an environmental temperature of 20 °C. To compute the hourly VR, the Q_{tot} was corrected for the measured hourly room temperature. In this paper, VR is expressed interchangeably as $m^3\ h^{-1}\ LU^{-1}$, $m^3\ h^{-1}\ HPU^{-1}$, or air change rate (ACH) (i.e., the number of times the building volume is refreshed with fresh air per hour, h^{-1}). The latter parameter, which is the quotient of the hourly volumetric flow rate in $m^3\ h^{-1}$ and the corresponding barn volume in m^3, standardises VR across the investigated buildings of various sizes and configurations, allowing for intercomparisons (Joo et al., 2015a,Joo et al., 2015b).

The measured temperature, RH, and gaseous concentrations were also computed on hourly basis, and the NH_3 and CH_4 emission rates (ER, g h^{-1}) were calculated as the product of VR and the gaseous concentrations using their hourly averages (Eq. 2).

$$ER = VR \cdot (C_{in} - C_{out}) \tag{2}$$

Where C_{in} and C_{out} (g m^{-3}) represent the indoor and outdoor gaseous concentrations, respectively. In buildings I and IV, C_{in}, was the measured gaseous concentrations in the exhaust duct, and C_{out} was the measured gaseous concentrations at the air inlet valve. C_{in} was calculated in building II as the average of the gaseous concentrations at the sample locations inside the building because the gaseous concentration at the ventilation duct could not be measured (Section 2.1). However, C_{out} was measured outside the building. In the naturally ventilated building, C_{out} was chosen as the lowest gaseous concentration measured at the two sidewall openings (Section 2.3.1) and C_{in} was calculated as the average of concentrations measured at the remaining sample location inside the building. It should be noted that in buildings II and III, the calculated C_{in} did not include sampling locations near the cows. Daily emissions were calculated as the average hourly emissions on days with hourly measurements $\geq$20 h. The calculated total hourly emission data was <24 in a day only three times in buildings II and III, and once in building IV, which was due to instrumental error. Thus, the total 24-hourly days at building I, II, III, and IV were 16, 11, 39, and 17, respectively. The NH_3 and CH_4 emission factors from each building were calculated by averaging all measured daily average emissions during the winter, spring, and autumn. In this study, gaseous emissions are expressed interchangeably as g $h^{-1}\ LU^{-1}$ or g $h^{-1}\ HPU^{-1}$, where 1 LU (livestock unit) = 500 kg.

2.4. Data analysis

In the current study, SigmaPlot 15.0 (Systat Software, San Jose, CA) was used for the scatter plots, simple linear regression and boxplot graphical comparisons, while Microsoft Excel Spreadsheet was used for the graphic presentations of diurnal variations in gaseous emissions and environmental parameters.

3. Results and discussion

3.1. Indoor climate and air exchange rate

3.1.1. Temperature

Fig. 2 illustrates diurnal variations in temperature, ACH and gaseous concentrations (NH_3 and CH_4) in the cattle buildings. The values shown are a consolidation of hourly data from the three measurement seasons, and the lines in the figures are moving averages of the hourly data in each building. During the day, hourly temperature variations in the buildings followed a sinusoidal curve, with minimum occurring around 5 a.m. and maximum occurring between 16 p.m. and 17 p.m. The peak and low temperature periods are consistent with Ngwabie et al. (2011), which were explained by animal activity, as animal heat production is highest during the day and lowest at night (CIGR, 2002). Furthermore, because outdoor temperature rises during the day and falls at night, external temperature influenced indoor temperature (Figure SM3a). Tables 1 shows the seasonal mean temperature, RH, ACH and gaseous concentrations in the buildings. The corresponding minimum and maximum values are shown in the Table SM5. Overall, the mean temperature in buildings I and II were within the set-point temperature at the climate control (Section 2). However, during winter, the mean temperatures in buildings III and IV were below 8 °C, whereas in autumn and spring, the temperatures in buildings III and IV were >14 °C, respectively. The reason was that during the measurements, buildings III and IV recorded colder and warmer outdoor temperatures than the other buildings. Only building III recorded sub-zero temperatures, even though the lowest outdoor temperatures were measured at building IV (Table SM5). This was because building III was naturally ventilated and semi-insulated. Indeed, when outdoor temperature was less than −12 °C, wall and floor temperatures in building III dropped below −2 °C, while temperatures in building IV, which was mechanically ventilated and fully insulated, remained above 0 °C (Figure SM4).

Figure SM3 illustrates the effect of outdoor thermal climate on temperature and RH inside the buildings. The slope and y-intercept of the regression lines demonstrate how insulation and ventilation control affect the thermal climate inside the different buildings. Comparing indoor and outdoor temperature difference (ΔT) during winter reveals that building IV was better insulated and ventilated less than building III, given that ΔT in building IV was greater than that of building III. Nonetheless, the hourly mean temperature in building III remained within the thermoneutral range of 5 °C to 25 °C throughout the measurement.

3.1.2. Relative humidity

In cold climates, moisture levels in livestock buildings are associated to ventilation performance. The combination of air temperature and RH that is outside of the thermoneutral limits not only affects animal performance but can deteriorate farm structures. For example, high levels of moisture during the winter are associated with the risk of condensation, which can deteriorate farm structures and promote pathogen

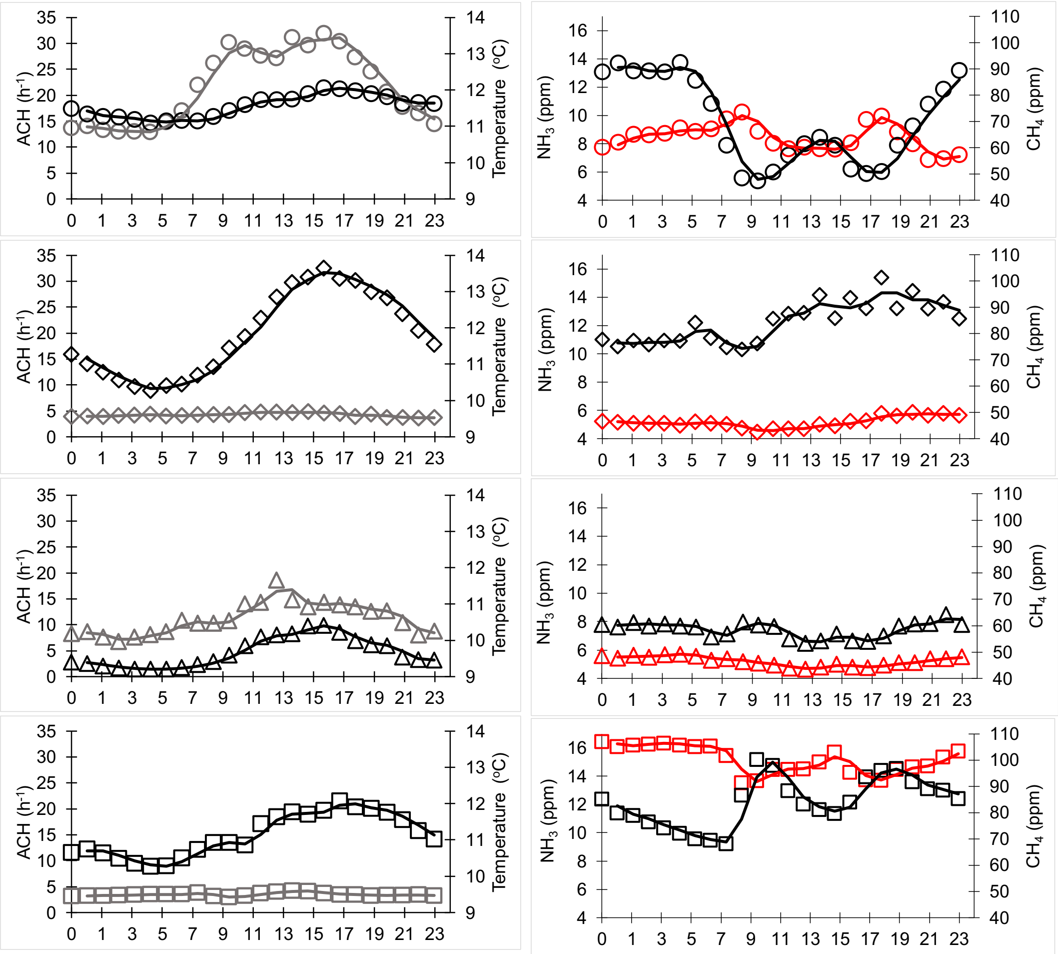

Fig. 2. Diurnal variations in ventilation rate (grey) & indoor temperature (black) NH_3 (red) & CH_4 (black) and concentrations in buildings I (○) (a &b), II (◊) (c &d), III (△) (e &f) and IV (□) (g &h).

Table 1
Hourly mean and standard deviation (SD) of temperature, indoor thermal climate, gaseous concentrations, and air exchange rate (ACH).

Building	*Season*	*Temperature (°C)*				*ACH (h^{-1})*		*Indoor concentration (ppm)*						*Indoor humidity (%)*	
		Outdoor		*Indoor*				*CO_2*		*NH_3*		*CH_4*			
		Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
I	Winter	1.6	2.9	10.5	0.8	17.8	8.4	1154	285	8.5	2.7	76	31	81	5
	Spring	5.7	1.7	11.4	0.9	25.4	12.1	872	124	6.2	1.1	46	13	64	6
	Autumn	3.1	2.3	12.5	0.9	24.2	12.9	1084	239	8.9	2.3	70	25	82	5
II	Winter	2.4	3.2	9.7	1.7	4.1	0.6	1025	89	6.2	0.7	83	13	81	6
	Spring	8.2	4.1	12.9	2.3	3.9	0.9	975	101	4.8	0.6	94	22	57	8
	Autumn	7	3.1	13.2	1.2	4.9	0.9	953	124	4.0	1.0	77	16	79	4
III	Winter	−1.1	3.8	7.9	1.9	5.3	3.3	1208	389	6.5	2.4	79	38	77	6
	Spring	4.9	3.3	9.0	2.1	14.2	7.3	655	95	2.6	0.8	26	9	59	10
	Autumn	12.4	2.3	14.5	1.7	21.7	16.6	581	65	3.1	0.9	19	6	75	8
IV	Winter	−9.9	2.6	7.1	0.5	1.7	0.3	1966	154	23.7	1.9	120	16	94	3
	Spring	11.0	3.0	15.6	1.7	5.4	1.0	909	135	5.8	1.0	44	13	76	8
	Autumn	2.1	1.8	10.4	0.5	3.1	0.5	1266	86	16.4	2.2	90	11	95	2

formation (Bleizgys and Bagdoniene, 2016). As a result, the CIGR (1984) recommends a RH range of 40 % to 80 %, with a maximum RH of <80 % at temperatures below 8 °C.

Table 1 shows that, apart from the suckler cow building (IV) in winter, the mean temperature and RH in all buildings were within the recommended ranges. According to Table SM5, there were also times during winter when temperature and RH in the naturally ventilated building (III) exceeded the recommended ranges. However, these extreme occurrences happened only for 3 h on the first day and an hour on the second day in building III, as opposed to 180 of 194 measurement hours in building IV.

Figure SM3b shows the relationship between indoor and outdoor RH. Among the mechanically ventilated buildings, outdoor RH explained only 39 % of the indoor variations of RH in building IV, compared to 99 % and 79 % in buildings I and II, respectively. The weaker correlation in building IV when compared to the other two mechanically ventilated buildings could imply that building IV was operating at minimum ventilation, and moisture generation from cows and evaporation from wet sources were more significant than in buildings I and II. And, under these conditions, the minimum ACH, which was <2 h^{-1} (Table SM5), was insufficient to maintain an acceptable indoor air quality. In fact, 94 % of the measured hourly RH in building IV was >90 % during winter and frequently reached near saturation levels. In addition, even though the mean ACH in autumn was 55 % higher than in winter, the RH remained >90 % (Table 1). Due to the cold climate, other studies have also identified unacceptable moisture levels as a major concern in mechanically ventilated livestock buildings in Norway (Bøe et al., 2017).

3.1.3. Gases

The diurnal variations in NH_3 concentrations in building I revealed that NH_3 concentration peaks coincided with feeding and manure scrapping schedules— i.e., when cow activity was high, and manure deposited on the slatted floor was disturbed by the farmer (Fig. 2b). However, this was not the case in building IV (Fig. 2g), which had a similar management routine as building I (Section 2.1 & 2.2). Nevertheless, the lows and peaks in NH_3 concentrations in both buildings coincided with ventilation rates. Diurnal variations in CH_4 and CO_2 (Figure SM5) concentrations were opposite to the NH_3 concentrations in buildings I and IV, but the diurnal variations in CH_4 and CO_2 concentrations in response to ventilation rate followed a similar trend in all the investigated buildings (Fig. 2). The results in buildings I and IV contradict the findings in buildings II and III (Figs. 2c & 2d and Figs. 2e & 2f), which show that increasing ventilation rate simultaneously reduces gaseous concentrations in livestock buildings.

The differences in diurnal trends of NH_3 and CH_4 concentrations with respect to ventilation rate in buildings I and IV can be attributed to differences in their production sources and factors influencing their production. For example, because enteric CH_4 from cows accounts for >80 % of the total CH_4 produced in cattle buildings, ventilation has minor effect on its production (Huang and Guo, 2018; Jungbluth et al., 2001; Ngwabie et al., 2011; Qu et al., 2021). However, NH_3 is primarily produced from slurry on the pen floors and/or in the slurry pit, and the mass transfer of NH_3 gas to bulk air is governed by local climatic factors such as air velocity and temperature, which are influenced by ventilation rate and airflow pattern (Groot Koerkamp et al., 1998). Therefore, increasing the ventilation rate in buildings I and IV may have increased the air speed and turbulence on the slatted floor and/or in the slurry pit, resulting in the higher NH_3 production than the other buildings.

Effects of inlet design could also be a factor because previous research with similar inlet type as buildings I and IV found higher NH_3 concentrations in the building with the higher ventilation rate (De Praetere and Van Der Biest, 1990). The reason was that the inlet type promoted an increased in air velocity on the pen floor, allowing the supply air to enter and transport NH_3 from the slurry pit. Such phenomena are more common when the supply air is colder than room temperature and buoyance force is greater than momentum force (Tabase et al., 2020; Tabase et al., 2018).

It is also hypothesised that the extremely high RH in building IV compared to the other buildings (Section 3.1.2) contributed to the increase in NH_3 volatilisation. This is because higher RH extends the life of wet surfaces, such as urine puddles, which continue to emit NH_3 even when ventilation rate is increased (Cortus et al., 2008). Furthermore, Hauge et al. (2012) previously reported that high RHs in Norwegian dairy cattle buildings, particularly during the cold winter months, were one of the major factors associated with cattle cleanliness. This is because poorly ventilated cattle buildings with high RH enhances condensation on surfaces during the winter, causing water droplets to drip on cows, resulting in damp bedding and animals. Therefore, the extremely high NH_3 concentration in building IV was not surprising, given that slurry-fouled cattle serve as an additional NH_3 production source.

In Fig. 3, NH_3 concentration profiles were used to assess airflow patterns in the buildings during the winter, when the supply air was cold. Because buildings I, III, and IV all had negative pressure slotted inlet systems, and building II had a different inlet type, Fig. 3 only compares the NH_3 concentration profile in building IV to that of building II. The results show that, unlike in building II, NH_3 concentrations increased from the floor to the ceiling in building IV, which is consistent with expected airflow patterns and agrees with what was observed during the smoke test. Indeed, the NH_3 concentration profile in building IV supports the above hypothesis, as such airflow patterns can increase air velocity and enhance NH_3 production from the emitting surface.

According to the Norwegian guidelines for livestock buildings (Fastsatt av Mattilsynet, 2020), the hourly mean CO_2 concentration in all the buildings never exceeded the maximum limit of 3000 ppm (Table 1). Building III had the lowest hourly mean CO_2 concentration

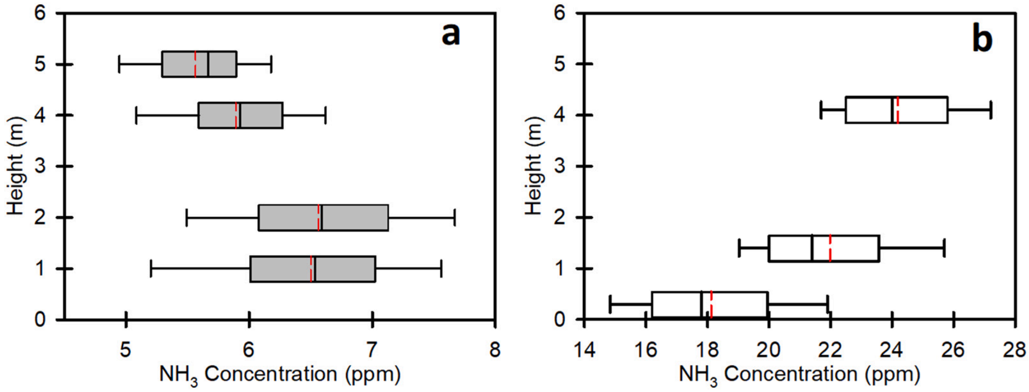

Fig. 3. Boxplots of NH_3 concentration profile at the feeding alley during the winter in (a) building II and (b) building IV. The median is indicated by the lines that divide the boxes, the mean by the red dash line, the minimum and maximum values are indicated by the whiskers.

(448 ppm) in the autumn, while building IV had the highest (2408 ppm) in the winter (Table SM5). As expected, the CO_2 concentration results mentioned above, correspond to the times when the highest (148 h^{-1}) and lowest ($1h^{-1}$) ACHs were measured, respectively.

The hourly mean NH_3 concentrations in buildings II and III rarely exceeded the maximum limit of 10 ppm, but not in buildings I and IV. The NH_3 concentrations exceeded the maximum limit in buildings I and IV during the winter and autumn when ACHs were low. During the winter and autumn measurements, 23 % and 28 % of the hourly mean NH_3 concentrations exceeded the maximum limit in building I, respectively. In contrast, the hourly mean NH_3 concentrations in building IV exceeded the maximum limit throughout the measurement period in winter and autumn. Apart from exceeding the recommended maximum limit, the hourly mean NH_3 concentrations also exceeded the long-term exposure limit of 25 ppm set by health and safety standards (Health and Safety Executive, 2020). That is, on six of the eight measurement days during the winter, the hourly mean NH_3 concentrations in building IV consistently exceeded the 25 ppm limit for an 8-h period.

To verify that building IV was operating in accordance with the recommended ventilation requirements in Norway (Gjestang et al., 1999), the overall ventilation rate was calculated using the recommended minimum ventilation requirements of 80, 45, and 15 m^3 h^{-1} per mature cow (> 600 kg), 400 kg young beef cow, and 100 kg calf, for a total of 74 cows. Figure SM6 shows that building IV was indeed ventilated above the minimum ventilation requirement of 60 m^3 h^{-1} cow^{-1}. However, the calculated minimum ventilation requirement, which is equivalent to an ACH of 1.2 h^{-1}, is nearly three and a half times lower than the recommended minimum ACH in North American cattle buildings (Joo et al., 2015a,Joo et al., 2015b). The unacceptable levels of RH and NH_3 in building IV during the winter, when compared to the indoor temperature, highlight the dilemma of maintaining a comfortable temperature for the calves by lowering the ventilation rate versus improving indoor air quality by ventilating more. Both of which can expose the calves to diseases and have an impact on feed efficiency (Mäkinen et al., 2009; van Leenen et al., 2020). It is also worth noting that, while ACH influences indoor climate, the type of ventilation system influences ventilation effectiveness and the interaction between supply air and pollutant production source. This is because, despite having similar ACHs (Table 1 & Table SM5), building II had lower NH_3 concentrations than building IV due to better air mixing and less airflow disturbance at the NH_3 emission source (Figs. 1 & 3). This highlights the need for novel ventilation systems in climates with longer winters that meet both the thermal and air quality needs of vulnerable livestock.

The highest CO_2 and CH_4 concentrations were measured during the winter in the buildings (I, III, and IV) with negative pressure, slotted inlet designs. The season with the highest ACH determined the season with the lowest CO_2 and CH_4 concentrations (spring or autumn). The effect of ACH on CO_2 and CH_4 concentrations during the different seasons was unclear in building II, especially between winter and spring. This was due to the type of ventilation system. The mean CO_2 and CH_4 concentrations observed were comparable to the 643–2925 ppm and 15–152 ppm ranges reported in dairy cattle buildings in cold climates, respectively (Cortus et al., 2015; Huang and Guo, 2018; Ngwabie et al., 2014; Ngwabie et al., 2011; Ngwabie et al., 2009; Teye et al., 2008). However, the CO_2 (454–607 ppm) and CH_4 (4.7–13.6 ppm) concentration ranges in the naturally ventilated dairy cattle buildings in Joo et al., 2015a,Joo et al., 2015b were in the lower range compared to this study.

The highest NH_3 concentrations were measured during the winter, as was the CO_2 and CH_4 concentrations (Table 1). The seasonal mean NH_3 concentrations in buildings II and III were within the concentration ranges reported by Ngwabie et al. (2009), Ngwabie et al. (2011) and Ngwabie et al. (2014), but higher than the concentrations (0.16–2.8 ppm) reported by Joo et al., 2015a,Joo et al., 2015b. The NH_3 concentrations in building I were also within the reported ranges of 2.2–23.0 ppm in Teye et al. (2008) and Huang and Guo (2017). In contrast, NH_3 concentrations in the suckler cow building (IV) were higher than previously reported concentrations for dairy cattle buildings in other cold climates.

3.1.4. *Air exchange rate*

Diurnal variations in ACH in buildings I and III followed similar patterns as indoor temperature (Figs. 2a & 2e). In both buildings, the highest ACHs were recorded during the day and the lowest at night. However, compared to building III, there were two maximum ACH peaks in building I, the first at 10:00 and the second at 16:00, which coincided with the feeding schedule in the building. Nonetheless, the overall diurnal ACH trends in buildings I and III were consistent with Ngwabie et al. (2011), as ventilation increases when indoor temperature rises and vice versa. In buildings II and IV, ACHs were instead high when the indoor temperature was low and vice versa (Figs. 2b & 2c). Such results are, however, not uncommon given that factors such as ventilation type, building insulation level, incorrect placement of temperature sensors, and the effect of management routines all have an impact on the diurnal variations in ventilation rate in livestock buildings (Pedersen et al., 1998).

Outdoor temperature influenced the magnitude of ACH in the buildings (Table 1 & Table SM5). As the lowest ACHs were recorded during winter and the highest was either in spring or autumn depending on the outdoor temperature. Building I had the most variable and highest ACH, followed by building III (Table 1 & Table SM5). Building III had a more variable ACH than the other buildings because it was naturally ventilated, and outside climatic factors such as wind speed influence airflow rate in naturally ventilated buildings (Figure SM7). Given that building I was mechanically ventilated and that external wind conditions have minor effect on ACH, it is unclear why the building had a higher overall mean ACH than building III (Table 1 & Figure SM7).

It was perhaps due to the more effective ventilation, as the variation in indoor air temperature was less when compared to the other buildings (Fig. 2a, Table 1 & Table SM5). Furthermore, when compared to the other buildings, the smaller building volume, narrower width (10–13 m), and lower ceiling height of 2.8 m (Fig. 1 & Table SM1) may have improved the ventilation effectiveness.

Figure SM7 presents scatter plots of external wind speed and ACH, as well as ΔT and ACH in buildings I and III. For the sake of brevity, only building I, representing the mechanically ventilated buildings, was compared to building III, which was naturally ventilated. As expected, the effect of external wind speed on ACH in building I was weaker than in building III (Figure SM4a & Figure SM4b). Only 16 % of variations in ACH in building III were explained by external wind speed in winter, compared to 43 % and 36 % in the spring and in autumn, respectively. The reason for this was that during the winter, when outdoor temperatures were below 0 °C, the sidewall curtains were opened to the smallest size (5 cm) to prevent indoor temperatures from freezing. This minimized the effect of external wind conditions on airflow while enhancing the influence of thermal buoyancy on airflow in the building (Figure SM7). Indeed, buoyancy effect appears to have also contributed to airflow in building I during the winter than the other seasons, when the inlet valves were also regulated to the smallest size and ventilation was low. Furthermore, it appears that thermal buoyancy contributed to the airflow in the naturally ventilated building in an equal proportion to the external wind during the spring and autumn seasons (Figure SM7).

3.1.5. Relationships between indoor climatic factors, air exchange rate, and temperature difference

Fig. 4 depicts the relationship between the daily average gaseous concentrations, RH and ACH, including ΔT. In general, increasing ACH reduced gaseous concentrations in the buildings (Figs. 4a - 4c). This was expected because increasing the ACH diluted the generated gases and provided fresh air to the building. The effect of ACH on RH followed a similar pattern as the gases, apart from building II, which demonstrated a positive correlation (Fig. 4d) This was most likely due to the building's ventilation system, as the system mixes the supply air streams with exhaust air before delivering it into the building (Section 2.1). Similarly, except for CH_4 in building II, the effect of ΔT on NH_3, CO_2 and RH showed a positive correlation.

The scatter plots show a linear relationship between ACH and gaseous concentrations, except for the naturally ventilated building, where a non-linear relationship begins to form at ACH $<6\ h^{-1}$ (Figs. 4a - 4c). The relationship in building III is identical to the naturally ventilated buildings in Joo et al. (2014), who used an inverse power relationship to describe the relationships between ventilation rate and, NH_3 and CO_2 concentrations. At ACH $>10\ h^{-1}$ and $<6\ h^{-1}$, it appears that the slopes in buildings I and IV can be superimposed on that of building III, respectively (Figs. 4a - 4c). This is because the recorded air change ranges (i.e., $1.0\ h^{-1}$ and $6.0\ h^{-1}$) when the slope in building IV is steep, coincide with the air change range in building III when the gaseous concentrations begin to show a non-linear relationship with ACH. Also, the recorded ACH ranges ($10.0\ h^{-1}$ and $30.0\ h^{-1}$) when the relationship between ACH and gaseous concentrations in building I is linear, fall within the ACH range in building III when the gaseous concentrations begin to have a linear relationship with the ACH.

Interestingly, the three buildings had jet air inlet designs, implying a similar airflow pattern. Therefore, it is not surprising that gaseous concentrations increased substantially particularly in buildings III and IV when the ACH was $<6\ h^{-1}$ and the outdoor temperature was less than −10 °C and ΔT was >10 °C. Given that under such conditions, buoyancy often prevail over momentum force causing the supply air to directly enter the slurry pit and transport the gaseous pollutant into the building (Braam et al., 1997; De Praetere and Van Der Biest, 1990; Tabase et al., 2020). However, due to the relatively high ventilation rates in building I during the winter, the effect of ΔT on gaseous concentrations particularly NH_3 was less pronounced than in buildings III and IV.

3.2. Diurnal and seasonal NH_3 and CH_4 emissions

Fig. 5 presents diurnal variations in NH_3 and CH_4 emissions in the buildings. The hourly variations in emissions differed between the buildings. For example, while diurnal variations in NH_3 and CH_4 emissions followed a similar pattern from 00:00 to 10:00 in building II, the NH_3 emission peak periods coincided with CH_4 emission low periods in buildings I, III, and IV. Diurnal variations in NH_3 and CH_4 emissions were primarily influenced by diurnal variations in ACH and gaseous concentration (Fig. 2) since emissions are the product of ventilation rate and the difference in indoor and outdoor gaseous concentrations (Eq. 2). According to Jungbluth et al. (2001), Ngwabie et al. (2011) and Zhang et al. (2005), management routine, ventilation type, temperature, and factors that influence NH_3 and CH_4 production can affect diurnal variations in emissions in cattle buildings. Thus, the differences in diurnal trends in emissions between the buildings in this study was probably caused by the differences in the above factors at the different farms. Further analysis also revealed that, regardless of the season, the diurnal trends in emissions were similar in the same building (Figure SM8).

Table 2 shows the seasonal mean NH_3 and CH_4 emissions in the buildings. Buildings I and III exhibited similar seasonal variations in NH_3 emissions. The increasing order of NH_3 emissions was from winter to spring and to autumn. In contrast, the highest NH_3 emission was during the winter in buildings II and IV and the lowest emissions were in autumn and spring, respectively. The seasonal differences in NH_3 emissions ranged from 22 to 38 %, 37–50 %, 67–81 %, and 2–112 % in buildings I, II, III and IV, respectively.

Overall, buildings I and IV had the highest NH_3 emissions despite having lower stocking densities (Table SM4) and smaller slatted floor area (Table SM1) than buildings III and II. Indoor NH_3 concentrations also followed a similar trend (Table 1 & Table SM5). The difference in manure handling can explain why buildings I and IV have higher NH_3 emissions than buildings II and III, because manure in buildings II and III were continuously scraped by robotic cleaners, whereas manure in buildings I and IV were manually scraped twice a day. We suspect that by continuously scraping the manure on the slatted floor, the urine puddle depth on the floor was reduced, resulting in faster puddle drying and, as a result, lower NH_3 generation compared to buildings I and IV. Indeed, Snoek et al. (2014, 2017) previously demonstrated that NH_3 emissions from cattle buildings were sensitive to the area and depth of a urine puddle since both parameters influence the NH_3 source size and the total amount of NH_3 available for emission.

Apart from building II, similar CH_4 was emitted during the three seasons in buildings I, III and IV. Seasonal difference in CH_4 emissions was from 2 to 7 % in buildings I, III and IV, whereas in building II the seasonal difference in CH_4 emissions ranged between 13 and 17 %. It was unclear why building II emitted the most CH_4, even though the cows consumed more concentrate per day (9.7 kg) than buildings I (9.1 kg) and III (7.9 kg). Furthermore, the overall daily average milk yield in building II (24.4 kg) was lower than building I (27.4 kg) and building III (25.7 kg). Because roughage consumption by the cows was not measured and no chemical analyses were performed during the investigation, the significance of the above values to enteric CH_4 production in the various buildings cannot be adequately explained. It was hypothesised that the greater CH_4 emissions in building II were caused by the building's ventilation system, in which air mixers kept some of the inside air and mixed it with fresh air. However, a look at the NH_3 (Table 2) and CO_2 (Table SM6) emissions challenged the assumption on the CH_4 emission. Contrary to the overall NH_3 emissions, the highest overall CH_4 was emitted in building II and the lowest in building IV. Finally, in addition to NH_3 and CH_4, CO_2 and N_2O emissions (Table SM6) were computed; however, CO_2 and N_2O emissions are only shown in the supplemental material because they are not the focus of this study.

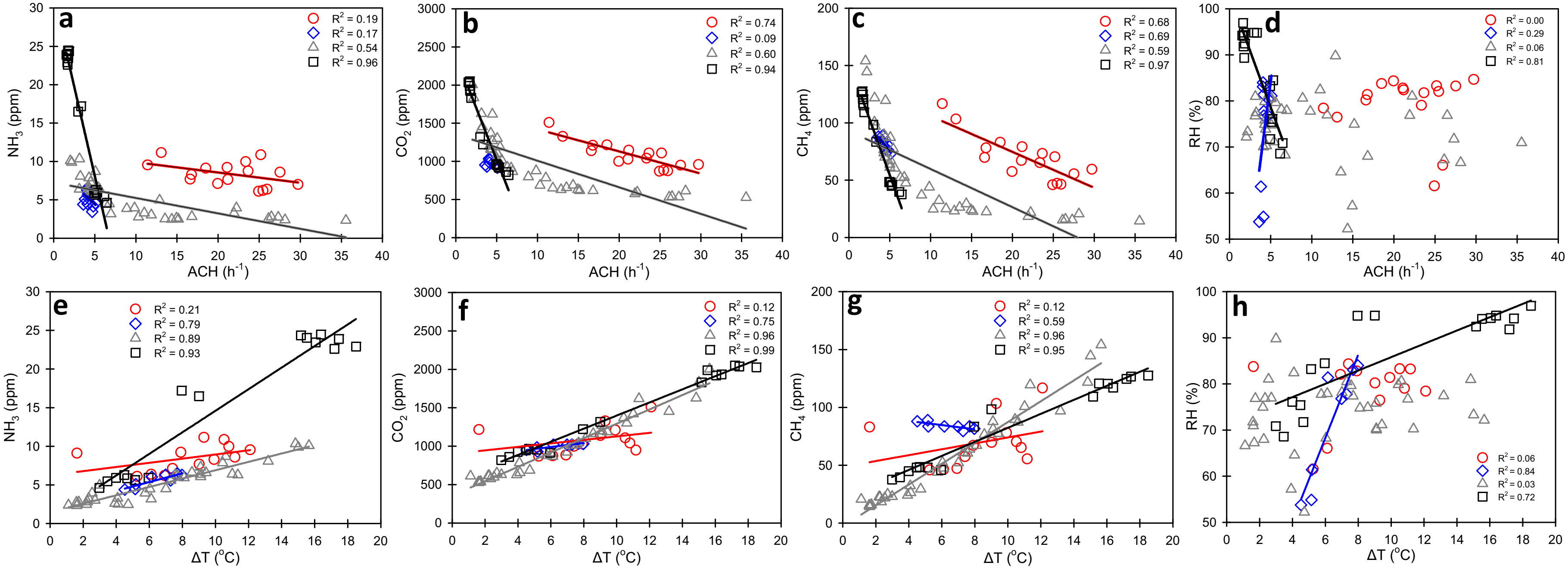

Fig. 4. Scatter plots of daily (a) NH_3 (b) CO_2 (c) CH_4 and (d) RH depended on ACH and (e) NH_3 (f) CO_2 (g) CH_4 and (h) RH depended on indoor and outdoor temperature difference (ΔT) in buildings I (○), II (◇), III (△) and IV (□).

3.3. Comparison of emission results with other studies

Table 3 compares the NH_3 and CH_4 emissions in this study to emissions in other cold climate regions. For comparison purposes, the unit used here is the livestock unit (LU). Furthermore, indoor temperature, ventilation rate, cattle number, type of cows and ventilation, and measurement seasons are provided. It should be noted that, while half of the cows in this study were calves and heifers, cows in the published literature were often mature. There were no recent published emission results for suckler cows in cold regions. Moreover, aside from Cortus et al. (2015), there were no recent emission measurements from mechanically ventilated buildings.

Except for Joo et al., 2015a,Joo et al., 2015b, the suckler cow building (IV) had lower CH_4 emissions than the dairy buildings. The lower CH_4 emission in Joo et al., 2015a,Joo et al., 2015bcompared to building IV was unexpected given that beef cows produce less CH_4 than dairy cows (IPCC, 2019). However, a look at the measured CH_4 concentrations reveals rather low overall mean concentrations in the two dairy cattle buildings (6.1 and 12.8 ppm, respectively) in Joo et al., 2015a,Joo et al., 2015bwhen compared to 85 ppm in building IV (Table 1). Building II emitted the most CH_4 when compared to the published emissions. In contrast, emissions from buildings I and III were within the published emission ranges.

The NH_3 emission range in building I was narrow, but it emitted more NH_3 than the published emissions except for (Schrade et al., 2012) and (Huang and Guo, 2017). Similarly, except for Schrade et al. (2012) and Huang and Guo (2017), the NH_3 emission range from the suckler cow building (IV) was wider than the other buildings, with the highest emissions in Autumn. Schrade et al. (2012) and Huang and Guo (2017) had higher NH_3 emissions than this study because measurements were taken during summer, which was not the case in this study. Indeed, during the summer, Schrade et al. (2012) and Huang and Guo (2017) measured higher ventilation rate and indoor temperature than in this study. Which is consistent with the widely held assumption that livestock buildings emit more NH_3 during the summer than during the winter due to higher ventilation rates and temperatures (Zhang et al., 2005). The NH_3 emissions from buildings II and III were within published emissions, despite Ngwabie et al. (2014) reporting lower emissions.

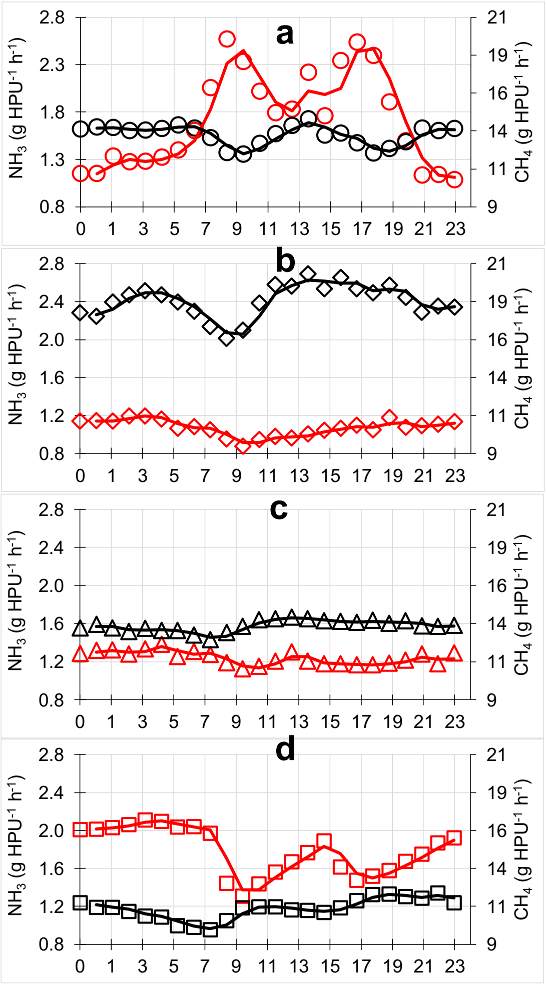

Fig. 5. Diurnal variations in NH_3 (red) and CH_4 (black) emissions in buildings I (○) (a), II (◊) (b), III (△) (c) and IV (□) (d).

Table 2
Seasonal mean and standard deviations (SD) of NH_3 and CH_4 emissions.

Building	Season	*Emissions (g HPU^{-1} h^{-1})*			
		NH_3		*CH_4*	
		Mean	SD	Mean	SD
	Winter	1.44	0.68	13.4	1.3
I	Spring	1.63	0.61	12.8	1.1
	Autumn	1.99	1.17	13.7	1.0
	Winter	1.29	0.18	17.6	1.4
II	Spring	0.94	0.14	20.6	2.7
	Autumn	0.86	0.27	18.0	1.9
	Winter	1.02	0.25	13.4	0.9
III	Spring	1.11	0.28	13.4	1.1
	Autumn	1.85	0.80	14.4	1.9
	Winter	2.20	0.34	10.6	0.6
IV	Spring	1.04	0.35	10.8	1.4
	Autumn	2.15	0.29	10.6	0.7

3.4. Relationships between NH_3 emissions and environmental factors

Fig. 6 illustrates the relationships between the daily NH_3 emissions and temperature, ΔT, RH, and ACH in the four cattle buildings. The data presented are a compilation of all measurement days taken during the three seasons. Overall, temperature influenced NH_3 emissions, but the direction of association between temperature and NH_3 emissions in buildings I and III was opposite to buildings II and IV (Fig. 6a). That is, while the correlation coefficients in buildings I ($R = 0.55$) and III ($R = 0.59$) were moderate and showed a positive temperature dependence, the correlation coefficients in buildings II ($R = -0.72$) and IV ($R = -0.82$) were relatively strong and showed a negative relationship between temperature and NH_3 emissions. Our results indicate that the correlation trends in buildings II and IV are inconsistent with previous studies (Hempel et al., 2016; Joo et al., 2015a,Joo et al., 2015b; Ngwabie et al., 2011; Schrade et al., 2012; Zhang et al., 2005).

Furthermore, the negative relationships contradict the theory of urease activity and the mass transport of NH_3 from manure following urea hydrolysis (Braam et al., 1997). This is because urease enzyme, which is responsible for urea hydrolysis, has low activity at temperatures below 10 °C and exponentially increases at temperatures above 10 °C (Braam et al., 1997). Moreover, it has been reported that the mass transport of NH_3 (via diffusion and/or convection) from the manure surface after urea hydrolysis increases with increasing temperature (Arogo et al., 1999; Cortus et al., 2008; Jeppsson, 2002).

Nevertheless, Tabase et al. (2018) reported a negative correlation between temperature and NH_3 emission. Their investigated building, like the current study, was mechanically ventilated and housed fattening pigs with an underfloor air inlet system. Tabase et al. (2018) attributed the negative temperature dependence on NH_3 emissions to the effects of air inlet design on airflow patterns and air exchange between the slurry pit and building volume, when relatively cold incoming air enters the slurry pit and forces NH_3 into the building. De Praetere and Van Der Biest (1990) observed a similar phenomenon in a more detailed study on

Table 3
Published NH_3 and CH_4 emissions, indoor temperature and ventilation rate compared to current investigation.

Country	Cattle & Ventilation type	Measurement Season	Cattle Number	Indoor Temperature (°C)	Ventilation (m^3 LU^{-1} h^{-1})	NH_3 emission (g LU^{-1} h^{-1})	CH_4 emission (g LU^{-1} h^{-1})
Building I	*Dairy & MV*	*Winter, Spring & Autumn*	*72–75*	*10.5–12.5*	*317–440*	*1.47–1.92*	*11.7–13.6*
Building II	*Dairy & MV*	*Winter, Spring & Autumn*	*102–114*	*9.7–13.2*	*319–339*	*0.78–1.26*	*16.4–19.3*
Building III	*Dairy & NV*	*Winter, Spring & Autumn*	*84–115*	*7.9–14.5*	*336–1608*	*0.98–1.61*	*13.3–13.8*
Building IV	*Suckler & MV*	*Winter, Spring & Autumn*	*61–74*	*7.1–15.6*	*84–280*	*0.68–2.04*	*6.8–10.7*
Sweden [1]	Dairy & NV	Winter & Spring	164–195	10.0–18.0	250–401	0.89–1.13	9.0–13.0
Sweden [2]	Dairy & NV	Winter & Spring	108	10.2 ± 4.5	520 ± 250	0.40–1.50	7.0–15.0
USA [3]	Dairy & NV	All seasons	400–850			0.63–1.53	
USA [4]	Dairy & NV	Summer & Autumn	250–850	11.0–34.0			2.8–10.5
USA [5]	Dairy & MV	All seasons	275–375		972–3074		9.0–13.8
Canada [6]	Dairy & NV	Spring & Autumn	210–221	7.4–10.3	531–824	0.43–0.64	12.2–13.9
Canada [7]	Dairy & NV	Winter, Summer & Autumn	112	5.1–28.0	143–1284	0.97–3.31	
Canada [8]	Dairy & NV	All seasons	112	6.0–24.0	107–1522		9.0–12.6
Switzerland [9]	Dairy & NV	All seasons	28–97	2.0–19.0		0.25–2.79	
Switzerland [10]	Dairy & NV	Autumn	40				11.1–13.2

[1] Ngwabie et al. (2009); [2] Ngwabie et al. (2011); [3] Joo et al., 2015a, Joo et al., 2015b; [4] Joo et al., 2015a,Joo et al., 2015b; [5] Cortus et al. (2015); [6] Ngwabie et al. (2014); [7] Huang and Guo (2017); [8] Huang and Guo (2018); [9] Schrade et al. (2012); [10] Bühler et al. (2021). Measurements were from two different cattle buildings in reference [3], [4] and [5]. NV and MV represent naturally and mechanically ventilated, respectively. Also, 1 LU = 500 kg.

the effects of slotted inlet systems on airflow patterns in a fattening pig building. They found that two secondary airflow patterns existed in the fully slatted building with a deep slurry pit—one remained above the slatted floor, and another extended into the slurry pit. Furthermore, the flow extending into the slurry affected the slurry temperature and forced NH_3 into the building. According to Braam et al. (1997), ΔT was a driving factor for slurry pit air exchange, with the highest NH_3 emissions observed when ΔT was positive and the lowest when ΔT was negative. Thus, the negative relationship between temperature and NH_3 emissions in buildings II and IV is due to greater air exchange between the slurry pit and the building than buildings I and III. Given that the relationships between ΔT and NH_3 emissions in buildings II (R = 0.85) and IV (R = 0.68) are stronger than in building I (R = 0.10) and building III (R = −0.54) (Fig. 6c) and follow a similar trend as in Braam et al. (1997).

There was an overall indication that ACH affected NH_3 emissions (Fig. 6b). The relationship between NH_3 emissions and ACH followed a similar pattern as the correlation between temperature and NH_3 emissions (Fig. 6a). There was a positive correlation between NH_3 emission and ACH in buildings I (R = 0.57) and III (R = 0.63), but not in buildings II (R = −0.30) and IV (R = −0.80). As with the correlation between temperature, ΔT, and NH_3 emissions, the correlation trends obtained for ACH in buildings II and IV were due to more complex factors such as airflow patterns. The buildings with positive NH_3 emission dependency on ACH had wider hourly ACH range (1–148 h^{-1}) than the buildings with negative NH_3 emission dependency on ACH (1–8 h^{-1}) (Table SM5). Previous research in naturally ventilated buildings with a wide range of ACHs (0–80 h^{-1}) found a positive NH_3 emission dependency on ACHs (Joo et al., 2015a,Joo et al., 2015b; Rong et al., 2014), which is

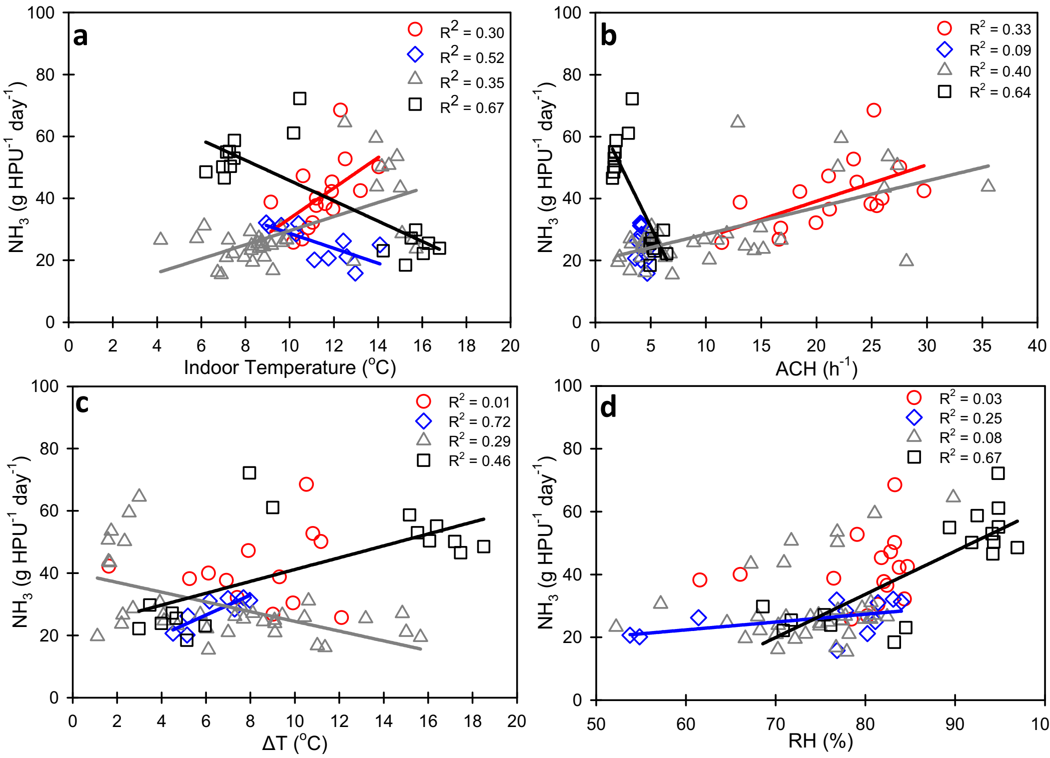

Fig. 6. Scatter plots of daily of NH_3 emissions depended on (a) ACH (b) indoor air temperature (c) indoor and outdoor temperature difference and (d) RH at buildings I (○), II (◊), III (△) and IV (□).

consistent with the findings in buildings I and III. Indeed, Rong et al. (2014) and Joo et al., 2015a,Joo et al., 2015b found that because their buildings were naturally ventilated, external wind speed influenced air velocity inside the buildings, which positively affected the overall ACH. Similarly, in this study external wind speed was found to be positively correlated with ACH in the naturally ventilated building (Figure SM7). There was no evidence, however, that external wind speed affected ACH in mechanically ventilated buildings (Figure SM7). The effect of ACH on NH_3 emissions is because higher ventilation rates often increase air speeds and promote turbulence over slurry surfaces, thereby increasing the mass transport of NH_3 via diffusion and/or convection (Cortus et al., 2008).

There was a positive correlation between indoor RH and NH_3 emissions in all the buildings (Fig. 6d). The correlation in building IV ($R = 0.82$) was stronger than building II ($R = 0.50$), whereas the correlations in building I ($R = 0.16$) and building III ($R = 0.28$) were weak. The positive humidity dependency on NH_3 emissions is inconsistent with findings of Saha et al. (2014)and Hempel et al. (2016) where they observed a decrease in NH_3 emissions as RH increases. They attributed their findings to the fact that NH_3 is water soluble, and that higher RH causes more NH_3 to be dissolved in moist air, resulting in less NH_3 generation (Huijsmans et al., 2001). However, Cortus et al. (2008) suggested that, in addition to RH, the area of wet surfaces (i.e., urine puddle) and the prevailing air velocity and temperature at the emitting surface influence NH_3 emissions. As a result, livestock buildings that have larger urine puddle areas combined with higher relatively humidity help sustain longer life of the wet surfaces, which continue to generate NH_3 even after increasing ventilation rate.

3.5. Relationships between CH_4 emissions and environmental factors

There was no clear temperature dependence on CH_4 emission in the mechanically ventilated buildings (Figure SM9a). The naturally ventilated building on the other hand, showed a moderately positive temperature dependency on CH_4 emission (R = 0.57). Also, apart from building II, which showed a strong negative ($R = -0.92$) relationship between RH and CH_4 emission, the other three buildings showed no clear RH dependence on CH_4 emission (Figure SM9d). For the relationship between ACH and CH_4 emission, the correlation coefficient in the suckler cow building ($R = 0.14$) was lower than in the dairy cattle buildings i.e. I ($R = -0.40$), II ($R = -0.34$), and III ($R = 0.66$) (Figure SM9b). There was also no clear ΔT dependence on CH_4 emissions in buildings I and IV, whereas the correlation coefficients were negative and strong in building II ($R = -0.90$) and weak in building III ($R = -0.50$) (Figure SM9c).

In general, there are contradictory reports regarding the impact of climatic factors on CH_4 emission in cattle buildings. This is because production of enteric CH_4, the main source of CH_4, is primarily influenced by feed type, amount consumed and animal production (Jungbluth et al., 2001). Zhang et al. (2005), Rong et al. (2014), and Huang and Guo (2018), for example, previously reported that climatic factors such as RH, temperature, and ventilation rate had no effect on CH_4 emissions in naturally ventilated dairy cattle buildings.

In contrast to the findings above, other studies conducted under a wide range of indoor temperatures (−9 to 36 °C), infer an indirect effect of one or more of the climatic factors on enteric CH_4 production (Hempel et al., 2016; Huang and Guo, 2018; Adviento-Borbe et al., 2010; Ngwabie et al., 2011; Saha et al., 2014; Schiefler, 2013). That is, indoor climate influences the thermoregulation and metabolism of cows, and the cows respond to thermal stress through animal activity and feed intake, which indirectly influences rumen activity and the enteric production of CH_4 (Ngwabie et al., 2011). Indeed, Ngwabie et al. (2011) found a positive correlation between CH_4 emissions and animal activity, which was inversely related to indoor air temperature in a cold climate. Furthermore, new evidence suggests that enteric CH_4 production in dairy cattle buildings has a parabolic temperature dependence (Hempel et al., 2016) rather than the linear dependence (Qu et al., 2021; Schiefler, 2013). The findings in Hempel et al. (2016) showed that CH_4 production was lowest when ambient temperatures was between 10 and 15 °C, while temperatures below 5 or above 15 °C resulted in an increase in CH_4 emissions. Implying that indoor climate control can be applied as a CH_4 mitigation strategy in cattle buildings.

In-house slurry is another source of CH_4. When compared to enteric CH_4, the proportion of CH_4 from in-house slurry varies greatly, ranging from 3 to 20 % (Kinsman et al., 1995; Marik and Levin, 1996; Ngwabie et al., 2014; Ngwabie et al., 2011; VanderZaag et al., 2014). The production of CH_4 from slurry, like that of enteric CH_4, is dependent on methanogens, which decompose volatile solids in slurry under anaerobic conditions (Sommer et al., 2007). As a result, the production of CH_4 from slurry is affected by retention time, temperature, volatile solids content, and the extent of anaerobic conditions in the stored slurry (IPCC, 2019). In cattle buildings where cow excrements are deposited on slurry already in the pit or on floors, CH_4 production can be immediate or within the first 10 days of storage, depending on whether methanogens are present in the stored slurry (Sommer et al., 2007). Furthermore, as slurry temperature rises, so does CH_4 production, with lower production at slurry temperatures below 10 °C (Pereira et al., 2011; Sommer et al., 2007). Finally, given that in-house, deep-pit slurry storage is the most common system in Norwegian cattle buildings where slurry is stored for an extended period, future studies should consider differentiating the proportion of total CH_4 emissions as enteric CH_4 and from slurry storage.

3.6. Limitations and implications

Ventilation rate is a key factor in calculating emissions from livestock buildings. Therefore, the method used have a significant impact on the accuracy of the estimated emission rate (Qu et al., 2021). The fan-wheel anemometer is the most reliable measurement method in mechanically ventilated buildings, with ±5 % accuracy depending on air speeds in the exhaust duct (VERA, 2018). However, the CO_2 mass balance method was used in this study to estimate ventilation rate in mechanically ventilated buildings because it was more practical given that the mechanically ventilated buildings had multiple exhaust ducts (Section 2.1). We used the CO_2 mass balance method in building III because there is currently no reference method for estimating ventilation rate in naturally ventilated buildings. The primary sources of error in the CO_2 mass balance method are a lack of knowledge of air inlet and outlet locations (in naturally ventilated buildings), the accuracy of CO_2 production from various animal categories, and the contribution from manure sources. The main limitation of this study is the inability to verify the accuracy of the CO_2 in calculating ventilation rate. Particularly in the naturally ventilated building and in building II, where the inlet and exhaust ducts were housed in the same housing (Section 2.1). In a subsequent study, it would be interesting to compare the CH_4 emissions with calculated CH_4 emissions using the IPPC Tier 2 modelling method. This will necessitate separating enteric and manure CH_4 emissions in each building so that the results can be adequately compared to the emission factors in the national inventory reports.

4. Conclusions

Measurements were taken in three commercial dairy and suckler cow buildings with different ventilation design and housing systems during three seasons of the year. The objectives were to assess indoor climatic conditions and report NH_3 and CH_4 emissions from Norwegian cattle buildings. The study also examined the effects of temperature, air change rate, and relative humidity on gaseous concentrations as well as NH_3 and CH_4 emissions. The study's findings include the following:

1. High relative humidity (RH > 90 %) was a major issue in the suckler cow building. Furthermore, only naturally ventilated building experienced sub-zero temperatures during the winter.
2. CO_2 concentrations in the buildings never exceeded 3000 ppm. However, during the winter and autumn, hourly mean NH_3 concentrations exceeded the long-term exposure limit of 25 ppm throughout the measurement period in the suckler cow building. The reason was that the minimum air change rate (ACH) requirement in Norway was three and a half times lower than North American cattle buildings.
3. The highest NH_3 emissions were recorded during the winter, but only in two buildings; the other two buildings had lower emissions when compared to spring and autumn. Seasonal differences in NH_3 emissions ranged from 22 to 38 %, 37 to 50 %, 67 to 81 %, and 2 to 112 %, respectively, in the four buildings.
4. Cattle buildings with lower stocking densities and smaller slatted floor areas emitted more NH_3 than buildings with higher stocking densities and larger slatted floor areas. Indoor NH_3 concentration levels followed a similar pattern. It was explained by differences in manure handling, as manure deposited on the slatted floor in the former buildings was manually scraped twice a day, whereas in the former buildings, robotic cleaners continuously scraped manure into the slurry pit.
5. Lowest CH_4 emissions were recorded in the suckler cows building (6.8–10.7 g LU^{-1} h^{-1}). Except for the dairy cattle building with the neutral pressure supply-exhaust air mixing system (16.4–19.3 g LU^{-1} h^{-1}), similar and lower CH_4 emissions were recorded in the other dairy cattle buildings (11.7–13.8 g LU^{-1} h^{-1}).
6. The suckler cow building had the highest NH_3 emissions (2.04 g LU^{-1} h^{-1}) followed by the dairy cattle building with the highest ventilation rate (1.92 g LU^{-1} h^{-1}). Furthermore, even though the current study did not include summer measurements, the NH_3 emissions in the two buildings were higher than those reported from other cattle buildings in cold climates.
7. Indoor temperature influenced NH_3 emissions; however, there were differences in the direction of association between daily average temperature and NH_3 emissions among the buildings studied.
8. There was a positive relationship between daily average RH and NH_3 emissions. However, the correlation coefficient was strongest in the suckler cattle building ($R^2 = 0.67$), which had the highest RH.

CRediT authorship contribution statement

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

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

The authors are unable or have chosen not to specify which data has been used.

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Appendix A. Supplementary data

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