

Article

Environmental and Animal-Related Parameters and the Emissions of Ammonia and Methane from an Open-Sided Free-Stall Barn in Hot Mediterranean Climate: A Preliminary Study

Provvidenza Rita D'Urso , Claudia Arcidiacono *  and Giovanni Cascone

Department of Agriculture, Food and Environment (Di3A), Building and Land Engineering Section, University of Catania, 95123 Catania, Italy; provvidenza.durso@phd.unict.it (P.R.D.); gcascone@unict.it (G.C.)

* Correspondence: carcidi@unict.it

Abstract: Increased knowledge on the factors that affect emissions from open-sided dairy buildings may lead to an improvement of the mitigation strategies. In this study, ammonia (NH₃) and methane (CH₄) emissions were assessed in an open dairy barn in a hot Mediterranean climate at different managements of the cooling system, as well as the influence of environmental and animal-related parameters on daily emissions. Measurements of gas concentrations and micro-climatic parameters were carried out in a cubicle free-stall dairy barn located in the province of Ragusa (Italy) in two weeks of 2016 characterised by similar climatic conditions in the warm period. Emissions of NH₃ and CH₄ were estimated through the application of the carbon-dioxide (CO₂) mass balance method. Data collected were organised in specific datasets to carry out different statistical analyses on gas emissions depending on selected parameters for the two weeks with a different management of the cooling system. The results showed higher NH₃ emissions and lower CH₄ emissions in W1 than those in W2. The variability in gas emissions was related to the effect of temperature humidity index (THI) ($p < 0.001$) and cow behaviour ($p < 0.01$). The highest emissions were recorded during the cleaning procedures for both NH₃ ($p < 0.001$) and CH₄ ($p < 0.001$), whereas the lowest emissions were recorded during the central hours of the day.

Keywords: open structure; cow behaviour; barn management; microclimatic conditions; cooling system; influencing parameters



Citation: D'Urso, P.R.; Arcidiacono, C.; Cascone, G. Environmental and Animal-Related Parameters and the Emissions of Ammonia and Methane from an Open-Sided Free-Stall Barn in Hot Mediterranean Climate: A Preliminary Study. *Agronomy* **2021**, *11*, 1772. <https://doi.org/10.3390/agronomy11091772>

Academic Editor: Pablo Martín-Ramos

Received: 14 July 2021

Accepted: 1 September 2021

Published: 3 September 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The emissions of ammonia (NH₃) and methane (CH₄) from the livestock sector have great environmental impacts. In 2017, manure management from dairy cattle produced 11% of the NH₃ emissions in the EU28 [1], whereas in 2015, the absolute emissions from the dairy cattle sector was 1711.8 million metric tonnes CO₂ equivalent; in particular, about 1100 was for CH₄ [2] derived from enteric fermentation and manure management. Increased knowledge on the factors that affect emissions from dairy buildings may lead to an improvement of the mitigation strategies for emissions reduction.

In Europe, dairy cows are mainly housed in naturally ventilated (NV) barns [3,4]. In these structures, which are characterised by large side openings, outdoor climatic parameters influence the indoor environment due to the high indoor-outdoor air exchange. In fact, the increase in outdoor temperature during spring and summer seasons in this housing system produces the highest emissions in the barn due to the increase in indoor temperature. As hot climate conditions produce heat stress on the cows [5–7], the NV barns are equipped with a cooling system (e.g., fans and sprinklers) to mitigate the effect of heat stress on the cows [8,9], especially in hot climate Mediterranean regions.

In the literature, many studies have been performed to assess the influencing parameters on gas emissions. Saha et al. [10] found that wind speed and wind direction, as well as

their interaction, had a significant influence on the air change per hour (ACH) ($p < 0.05$). Ngwabie et al. [11] studied the effects of animal activity and air temperature on methane and ammonia emissions. They found that daily CH_4 emissions increased significantly with the activity of the cows ($r = 0.61$) and decreased when the indoor air temperature increased ($r = -0.84$), whereas daily NH_3 emissions increased significantly with the indoor air temperatures ($r = 0.66$). In the meta-analysis carried out by Poteko [12] in the 'loose housing system with cubicles' category, air temperature influences both NH_3 ($p < 0.001$) and CH_4 ($p < 0.001$) emissions. The analysis carried out by Hempel et al. [13] showed a nonlinear temperature dependency of NH_3 and CH_4 emissions, as well as the increase in NH_3 emissions due to the higher wind speed and lower relative air humidity values compared to the night.

According to Bohmanova et al. [14], the combination of environmental parameters (e.g., temperature, relative humidity, solar radiation, air movement and precipitation) can cause heat stress in cows with a consequent reduction in milk production. In the study of Hempel et al. [4], the total loss was estimated to be about 2.8% compared to the present European milk yield, due to the expected increase in heat stress events associated with a threshold of temperature humidity index (THI) greater than 72. This latter index is an indirect parameter of heat stress based on the values of air temperature and relative humidity [15,16]. Heat stress, as well as the management of the cooling system, significantly influences cow behaviour and time spent lying or standing [9,17,18]. In the literature, the evaluation of cow behaviour has generally been carried out by using cow behavioural indices, i.e., cow lying index (CLI), cow standing index (CSI) and cow feeding index (CFI) [19,20]. These parameters were useful to assess the cow behaviour under different climatic conditions and cooling sessions.

Although the influence of climatic conditions on emissions, as well as the influence of heat stress on cow behaviour, has been investigated in the literature, there is a lack of evaluation of the connections between animal-related parameters (e.g., THI and cow behavioural indices) and gas emissions under hot climate conditions. Therefore, the aim of the present study was to fill this gap by pursuing the following objectives: (1) evaluating daily emissions of NH_3 and CH_4 ; (2) studying the influence of THI on gas emissions; (3) assessing the effect of cow behaviour variations on gas emissions. In this study, it was hypothesised that a different management of the cooling system under hot climatic conditions can influence the NH_3 and CH_4 emissions in the barn due to the modification of the microclimatic parameters and cows' behavioural activities.

2. Materials and Methods

2.1. Experimental Barn and Period of Investigation

The study was conducted in a cubicle free-stall dairy barn located in Pettineo/Pozzilli (37°01' N, 14°32' E) in the province of Ragusa (Italy), which is an area characterised by the highest number of dairy farms within Sicily [21]. With an average air temperature of 15.1 °C and rainfall of 679 mm in 2016 (SIAS), the climatic conditions in Ragusa are representative of a hot summer Mediterranean climate, classified as Csa in the Köppen classification. The periods of investigation covered two weeks, week 1 (W1) from 15/06 to 21/06 and week 2 (W2) from 01/07 to 07/07, characterised by homogeneous climatic conditions and a different barn management, as reported in Section 2.3.

The barn facility was about 55.50 m long and 20.80 m wide. The dairy house building was composed of three sides (i.e., the SE, NE and NW sides) completely open, whereas the SW side was closed by a continuous wall with four small openings (i.e., 0.90 m × 2.10 m). The symmetric roof, made of fibre-reinforced concrete corrugated panels, had a central 7 m-high ridge vent and a 4 m-high eave. The barn was composed of three pens on a concrete floor equipped with 64 head-to-head cubicles (Figure 1). The cubicles were arranged in two rows with concrete kerbs, covered with sand.

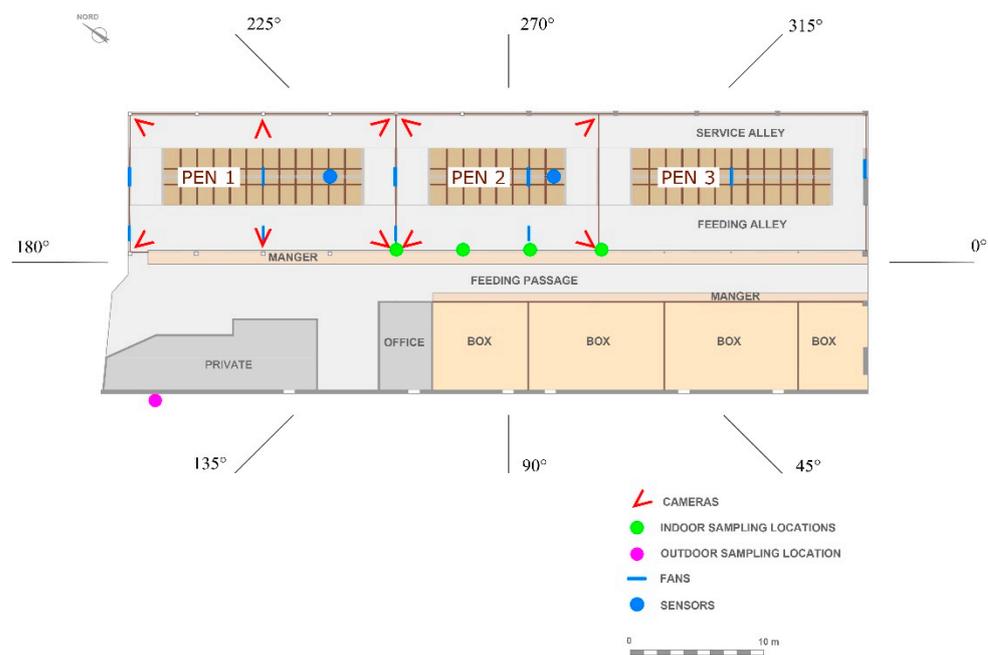


Figure 1. Plan view of the barn and position of sampling locations, cameras, fans and sensors.

The natural ventilation system was integrated by two cooling systems, composed of a fogging system with fans, located in the resting area, and a sprinkler system with fans, located in the feeding alley. In detail, the fans in the resting area had a width of 1400 mm, tilt angle of 20° from the horizontal and a ventilation rate of 34,600 m³/h. The rotation axis was located at 2.75 m from the floor along the longitudinal axis of the barn, and the distance between fans was equal to 14.0 m. The fogging system in the resting area was composed of misters having an operating pressure of 200 kPa and the corresponding rate of 1.01 L/min for each nozzle. They were located at a height of 2.90 m from the floor and spaced about 3.10 m along the longitudinal axis of the barn. The half-circle (180°) sprinklers in the feeding alley had an operating pressure of 200 kPa and a rate of 2.57 L/min. The sprinklers were installed above the rack at a 2.0 m height from the floor along the longitudinal axis of the feeding alley with a 1.90 m spacing. Each axial fan in the feeding alley had a diameter of 900 mm, tilt angle of 20° from the horizontal and a ventilation rate of 22,250 m³/h. The five axial fans were located above the feeding alley with the rotation axis at 2.70 m from the floor and parallel to the longitudinal axis of the feeding alley. The distance between fans in this row was 14.0 m.

2.2. Measurement of Gas Concentrations and Climatic Parameters

Concentrations of NH₃, CH₄ and carbon dioxide (CO₂) were continuously acquired at five sampling locations (SLs) by an INNOVA photo-acoustic analyser composed of a Multigas Monitor mod 1412i and a multipoint sampler 1409/12 (Lumasense Technology A/S). The five inlet channels were made of PTFE (polytetrafluoroethylene) tubing to reduce the adsorption of samples. The end of each sampling tube had an air filter to keep the 1409 free of particles. The accuracy of the Multi-Gas Analyser involved a 2–3% absolute deviation in concentrations, and the detection limits were 0.2 ppm for NH₃, 0.4 ppm for CH₄ and 1.5 ppm for CO₂. The SLs were located in different areas of the barn. The location of the four indoor SLs was in the central area of the barn at 20 cm from the barn floor. The background concentrations were recorded in an outdoor SL, located at 3 m above the floor outside the barn and upwind at 2 m from the front of the barn. Gas concentrations were measured with a sampling frequency of 15 min for each SL. The INNOVA analyser was calibrated by the manufacturer just before the measurements. The setup of INNOVA had a sample integration time of 5 s.

Climate and microclimatic parameters were measured by sensors installed inside the barn at 2.0 m above the floor and outside the barn above the roof along the ridge. Air temperature, relative humidity, indoor air and wind speed and direction were acquired with a frequency of five seconds by a data-logger CR10X (Campbell, UK) that, every five minutes, computed the average values and stored them in memory locations. Air temperature (Rotronic Italy s.r.l., Milano, Italy) was measured by platinum thermo-resistances (Pt 100 Ω 0 °C) characterised by a measurement range between -40 and $+60$ °C and a precision of ± 0.2 °C (at 20 °C), whereas air relative humidity was measured by an hygrometer (Rotronic Italy s.r.l., Milano, Italy) with a sensitivity of $\pm 0.04\%$ RH/°C and a precision of $\pm 2\%$ (at 20 °C). The anemometers (WindSonic, Gill instruments Ltd., Lymington, UK) with two-dimensional sonic sensors had a velocity measuring interval of $0-60$ m s⁻¹, a precision of $\pm 2\%$ (at 12 m s⁻¹), a resolution of 0.01 m s⁻¹ and a threshold of 0.01 m s⁻¹; and had a direction measuring interval of $0-359^\circ$, with a precision of $\pm 3\%$ (at 12 m s⁻¹) and a resolution of 1° .

2.3. Barn Management and Behavioural Activity Recordings

Sixty-four Fresian cows were housed in the cubicle free-stall barn with an average weight of 643 (± 72) kg and milk yield of 37.2 kg/day. During the trial, the diet of the cows, based on a mixed ratio with concentrate, was the same in both weeks. The activation of the sprinklers and fans was not simultaneous and the activation time is reported in Table 1. In detail, the fans were automatically switched off during wetting to avoid the scattering of water. The cooling systems were manually switched off during the milking sessions and the cleaning of the feeding alley. During the two weeks of observation, the management of the cooling system was different. In detail, the sprinklers in the feeding alley were not operated in W2. The daily routine of the cows was further affected by the barn management. In detail, the cleaning of the barn was carried out once a day at about 07:30 a.m. by a mechanical tractor with scraper; the milking session was performed twice a day at about 5:00 a.m. and 5:00 p.m.; the feed was delivered every day after cleaning, and it was moved into the manger before the first and the second milking sessions.

Table 1. Timetable of the two cooling systems in the two weeks.

System	Area	Activation Time
Fans	Feeding area	8.30–9.00
Sprinkler system with fans	Feeding area	9.00–11.00
Fogging system with fans	Resting area	11.00–16.00
Sprinkler system with fans	Feeding area	16.00–17.00
Sprinkler system with fans	Feeding area	18.30–20.00
Fans	Resting area	20.00–1.00

A 24 h video-recording system, composed of ten cameras (Kon.Li.Cor, Perugia, Italy), recorded cow behaviour during the experiment in pen 1 and pen 2 (Figure 1). Based on the visual evaluation of the records, the scan sampling method [22] was applied with a frequency of 15 min in order to assess animal behaviour in pen 1 and pen 2 (i.e., forty cows were observed with cameras). Under this method, a skilled operator counted the number of cows in a specific behaviour (i.e., feeding, lying and standing) in each frame of the video recordings and stored them in a spreadsheet. Then, the CFI, CLI and CSI were computed [19]. In detail, the CLI was determined by counting the number of cows in lateral or sternal recumbence inside the stall and applying the following relation: $CLI = (\text{Cows Lying in Stall}) / (\text{Total Cows})$. The CSI, related to the number of cows in upright posture, walking included, was determined by the following equation: $CSI = (\text{Cows Standing in Stall}) / (\text{Total Cows})$. The CFI, based on the number of cows that ingest feed or water, was evaluated with the equation: $CFI = (\text{Cows Feeding in Stall}) / (\text{Total Cows})$.

2.4. Air Exchange Rate and Emissions Calculations via Indirect Method

In this study, the estimation of NH₃ and CH₄ emissions was carried out by applying the CO₂ mass balance method [3,10,23]. The ventilation rate Q (m³ h⁻¹) was calculated as follows:

$$Q = P_{\text{CO}_2} \times N / (C_{\text{CO}_2\text{in}} - C_{\text{CO}_2\text{out}}) \quad (1)$$

where P_{CO₂} represents the excretion rate of CO₂ from one cow (g cow⁻¹ h⁻¹), N is the number of cows housed inside the building, and C_{CO₂in} and C_{CO₂out} are the hourly average concentrations of the gas inside and outside the building in the prevailing air direction, respectively (g m⁻³).

Within the CO₂ balance, the CO₂ excretion rate depends on animal heat production. As, in this barn facility without deep litter, the CO₂ production from manure is below 4% of the total production [24,25], the CO₂ excretion rate was computed as follows [26]:

$$q_t = 5.6 \times m^{0.75} + 1.6 \times 10^{-5} \times p^3 + 22 \times y \quad (2)$$

$$CF = 4 \times 10^{-5} \times (20 - T_i)^3 + 1 \quad (3)$$

$$q_{\text{cor}} = q_t \times CF \quad (4)$$

$$P_{\text{CO}_2} = 0.299 \times q_{\text{cor}} \quad (5)$$

where q_t is the total heat production (W), m is the average mass of the animals (kg cow⁻¹), p is the number of days after insemination (d), y is the milk yield (kg d⁻¹), CF is the temperature correction factor, T_i is the temperature inside the building (°C) and q_{cor} is the corrected value of the total heat production (W). The average weight, milk yield of the cows and contribution of pregnancy were 650 kg cow⁻¹, 32 kg d⁻¹ and 135 days, respectively.

The emission rate of NH₃ and CH₄ was estimated using the following equation:

$$E_t = Q \times (C_{\text{in}} - C_{\text{out}}) \quad (6)$$

where E_t is the emission rate of the gas (g h⁻¹), Q is the ventilation rate calculated according to the CO₂ balance method (m³ h⁻¹), and C_{in} and C_{out} are the average concentrations of the gas inside the barn (i.e., average value of the 4 indoor SLs) and outside the building (Figure 1), respectively (g m⁻³). The weight of the cows and the production may differ from herd to herd. In order to make the results comparable with other studies, the emissions E_t were computed as the emissions per livestock unit (LU) in g h⁻¹ LU⁻¹, where LU is equivalent to a 500 kg animal mass. The emission rate per LU is estimated as follows:

$$E = (E_t \times \text{LU}) / (N \times m) \quad (7)$$

2.5. Data Analyses

Data were analysed by using Microsoft[®] Excel and Minitab software. Statistical analyses were carried out to assess the influence of a different management of the cooling system in the two weeks. For each week, the influence of THI and cow behaviour on daily gas emissions was analysed. The THI was computed according to Hempel et al. [27]:

$$\text{THI} = (1.8 \times T + 32) - [(0.55 - 55/100 \times \text{RH}) \times (1.8 \times T - 26)] \quad (8)$$

where T is the dry bulb air temperature (°C) and RH is the relative humidity (%).

Gas emissions were subdivided considering the following groups of THI: comfort zone (THI ≤ 72); low risk of thermal stress for cows (72 < THI ≤ 78); thermal stress (78 < THI < 84). As conditions of emergency for cows (THI ≥ 84) were not recorded in this study, emissions for emergency conditions were not analysed.

The influence of cow behaviour on hourly gas emissions was analysed by using the CLI and the cow activity index (CAI), computed as the sum of CFI and CSI. For each value of gas emissions, a specific cow behaviour (i.e., cow activity and cow lying) was associated.

The cow lying condition is related to emissions when cows are resting in the cubicles for a mean value of CLI > 0.50 for each hour. The cow activity condition includes gaseous emissions produced when cows are standing, feeding and walking for a mean value of CAI > 0.50 for each hour. As, during the cleaning of the floor, gas concentrations and emissions were found the highest [28,29], an additional group, named barn cleaning, was considered. Barn cleaning refers to the dataset of gas emissions with a mean value of CAI > 0.50 for each hour that is related to the cleaning of the floor (i.e., when cows are either feeding or standing or walking).

The statistical analyses were carried out by using gas emissions in the prevailing air direction from North-West (135–225°), which represented about the 85% of the whole dataset. Moreover, the final dataset of gas emissions was composed of the values that excluded gas emissions under complex windy conditions [23], which represented about 1% of the dataset in the prevailing air direction. In detail, CO₂ differences lower than 100 ppm were neglected to reduce biases in the emission values. After checking the assumptions, a one-way analysis of variance (ANOVA) was applied to the above-described groups of NH₃ and CH₄ emissions. The level of significance was defined by a *p* value of 0.05. If the test result was significant, the Tukey test post hoc analysis was applied in order to identify differences between groups of gas emissions.

3. Results and Discussion

The results showed a daily variation in NH₃ and CH₄ emissions due to the microclimatic conditions and barn management. The different management of the cooling system in the two weeks under study modified the cows' behaviour in response to heat stress. Consequently, the NH₃ and CH₄ emissions in the barn were significantly different in the two weeks analysed. The choice of the two weeks is related to the identification of two periods with homogeneous microclimatic conditions in the barn. In fact, microclimatic parameters (i.e., air temperature, air velocity and relative humidity) were not significantly different (*p* < 0.001) in both W1 and W2. In this way, the difference between the two periods was due to the different management of the cooling system. The outcomes of this study constitute preliminary information for the computation of emissions from the open-sided dairy barn, through the increase in knowledge on how gas emissions, through environmental and animal-related parameters, are influenced by different managements of the cooling system.

3.1. Daily NH₃ and CH₄ Emissions

The mean NH₃ emission rate in W1 was 4.73 g LU⁻¹ h⁻¹ with an indoor average temperature of 26.3 °C and an air velocity of 0.71 m s⁻¹, whereas the mean NH₃ emission rate in W2 was 5.90 g LU⁻¹ h⁻¹ with an indoor average temperature of 27.5 °C and an air velocity of 0.69 m s⁻¹. The hourly average NH₃ emissions were 0.85 to 11.25 g LU⁻¹ h⁻¹ in W1 and 1.64 to 10.86 g LU⁻¹ h⁻¹ in W2. The values of NH₃ emissions found by other studies [3,30] are slightly lower than those found in this study due to the different climate conditions of the countries and the barn management.

Based on the results of the one-way ANOVA, NH₃ emissions in W1 were significantly different (*p* < 0.001) from those in W2 with higher NH₃ emissions in W2. As the sprinkler system in W2 was not operated, the emissions in W2 were higher due to the lack of the dilution effect of water on NH₃. In fact, the presence of water on the floor reduces the pH of the pure urine necessary for the NH₃ formation and, consequently, the emissions decrease [31]. Moreover, even though there was not a significant difference between air temperatures in W1 and those in W2, the mean value of air temperature in W2 was slightly higher than that in W1. This is one of the main influencing factors of the increase in NH₃ emissions as it was found in previous studies [13,30].

The mean CH₄ emission rate was 5.85 g LU⁻¹ h⁻¹ in W1 and 5.52 g LU⁻¹ h⁻¹ in W2. The hourly-averaged CH₄ emission values were 2.40 to 8.83 g LU⁻¹ h⁻¹ in W1 and 2.89 to 9.53 g LU⁻¹ h⁻¹ in W2. The results of the one-way ANOVA showed that there is

a significant difference ($p < 0.009$) between CH_4 emissions in W1 and CH_4 emissions in W2 with higher CH_4 emissions in W1 than those in W2. This result can be explained by the different management of the cooling system between the two weeks. In fact, when the sprinklers were not operated in W2, the CFI reduced from 0.28 in W1 to 0.25 in W2 and, therefore, the time spent at feeding was lower in W2 compared to that in W1 (Table 2). Conversely, the time spent lying increased in W2 with a CLI increase from 0.49 in W1 to 0.53 in W2. The different animal behaviour was related to the response to heat stress [32] that increases from W1 to W2. In detail, the THI in W2 was significantly different than that in W1 ($p = 0.007$) with a higher THI in W2 (Table 2). In the literature, it was found that the time spent at feeding reduces the dry matter intake (DMI) [33] and that there is a high correlation between CH_4 production and DMI [34]. Therefore, the reduction in CH_4 emissions in W2 found in this study could be attributed to a reduction in DMI in response to heat stress. Moreover, it can be highlighted that while cows generally spend more time standing than lying under stress conditions to favour heat dissipation [17,18], in the barn under study, the presence of the fogging system in the resting area increased cow comfort and, thus, the time spent lying increased [8,9].

Table 2. Weekly mean values of the air velocity (v), temperature humidity index (THI) and behavioural indices (i.e., CLI, CSI and CFI) computed between 1 h intervals in both W1 and W2.

Hour	v		THI		CLI		CSI		CFI	
	W1	W2								
0	0.51	0.82	68.5	71.2	0.68	0.68	0.16	0.18	0.15	0.14
1	0.58	0.61	69.8	69.9	0.66	0.66	0.23	0.21	0.11	0.13
2	0.55	0.45	68.5	69.2	0.69	0.62	0.15	0.13	0.16	0.25
3	0.45	0.36	67.6	68.9	0.69	0.65	0.20	0.21	0.10	0.14
4	0.47	0.34	67.6	67.4	0.78	0.77	0.16	0.17	0.06	0.06
5	0.34	0.31	66.9	67.0	-	-	-	-	-	-
6	0.35	0.29	66.9	67.3	-	-	-	-	-	-
7	0.37	0.33	70.2	70.9	0.11	0.15	0.14	0.17	0.75	0.68
8	0.54	0.38	74.1	75.2	0.08	0.26	0.44	0.42	0.47	0.32
9	0.57	0.51	77.1	77.1	0.26	0.23	0.11	0.26	0.63	0.52
10	1.12	1.23	77.4	78.3	0.42	0.61	0.28	0.23	0.30	0.16
11	1.25	1.28	77.0	79.4	0.70	0.82	0.22	0.16	0.08	0.01
12	1.18	1.21	78.6	80.6	0.60	0.71	0.29	0.26	0.11	0.02
13	1.16	1.21	78.9	80.8	0.58	0.73	0.34	0.13	0.08	0.14
14	1.18	1.16	79.0	81.1	0.48	0.68	0.30	0.23	0.22	0.09
15	0.82	0.62	79.0	80.5	0.27	0.10	0.16	0.10	0.58	0.80
16	0.65	0.46	78.3	79.8	0.08	0.09	0.14	0.30	0.78	0.61
17	0.92	0.49	77.8	78.6	-	-	-	-	-	-
18	0.78	0.38	77.1	77.9	-	-	-	-	-	-
19	0.56	0.40	75.8	77.1	0.22	0.28	0.23	0.32	0.55	0.41
20	0.38	0.34	73.1	75.8	0.54	0.46	0.31	0.27	0.15	0.27
21	0.95	1.11	71.6	73.9	0.68	0.71	0.27	0.19	0.06	0.10
22	0.71	1.02	70.4	72.6	0.56	0.72	0.32	0.20	0.12	0.08
23	0.68	0.93	69.9	71.7	0.63	0.69	0.25	0.15	0.12	0.16
Mean	0.71	0.68	73.4	74.7	0.49	0.53	0.24	0.21	0.28	0.25

The NH_3 and CH_4 emissions changed hourly during the day where several peaks occurred, as it was found by Ngwabwe et al. [35]. Daily variations in NH_3 and CH_4 emissions in both W1 and W2 are shown in Figure 2. Whereas the trend of NH_3 emissions is similar in both weeks, the trend of CH_4 emissions in W2 is more variable than that in W1 due to the indirect effect of the cooling system on the animal feeding behaviour. In detail, NH_3 emissions reached the highest emissions during the early morning and late afternoon, whereas the lowest value occurred at 16.00 in both W1 and W2. The higher air velocity (Table 2) and the activation of the cooling system (Table 1) during the central hours of the day diluted concentrations in the environment with an effect on the emissions. Concerning

CH₄ emissions showed different peaks during W1 and W2 with lower emissions in the central hours of the day (i.e., 12.00 and 15.00) as for NH₃. One of the main influencing factors on emissions, deriving from the utilized model, is the ratio between the differences in measured outdoor and indoor concentrations of CO₂ ($C_{CO_2in} - C_{CO_2out}$) and gas pollutants (i.e., $NH_{3in} - NH_{3out}$ and $CH_{4in} - CH_{4out}$) [36]. It is recognized, in fact, that variations in gas concentrations can be influenced by several factors, such as diet, climatic parameters and barn management [10,22,37,38], producing effects on related emissions. Figure 3 shows the daily trend of the difference between $NH_{3in} - NH_{3out}$, $CH_{4in} - CH_{4out}$ and $C_{CO_2in} - C_{CO_2out}$ in both weeks. In detail, the ratio between ($NH_{3in} - NH_{3out}$) and ($CO_{2in} - CO_{2out}$) was low during the central hours of the day, from about 10.00 to 16.00, due to the lowering of the NH₃ concentration difference, while the CO₂ difference showed a constant trend. The same effect was detected for CH₄, yet to a less extent compared to that of NH₃. The similar trend of the daily differences for CH₄ and CO₂ due to their correlation [22] produced an almost constant CH₄ emission throughout the day, especially in W1 (Figure 2). Conversely, NH₃ emissions showed two peaks deriving from the trend of the NH₃ difference dampened by the trend of the CO₂ difference that was almost constant until 14.00 and higher until 21.00. The interquartile ranges showed that the values in W1 had a higher variability than those in W2 for concentration differences, whereas those ranges for emissions were uniform in the two weeks, especially for CH₄.

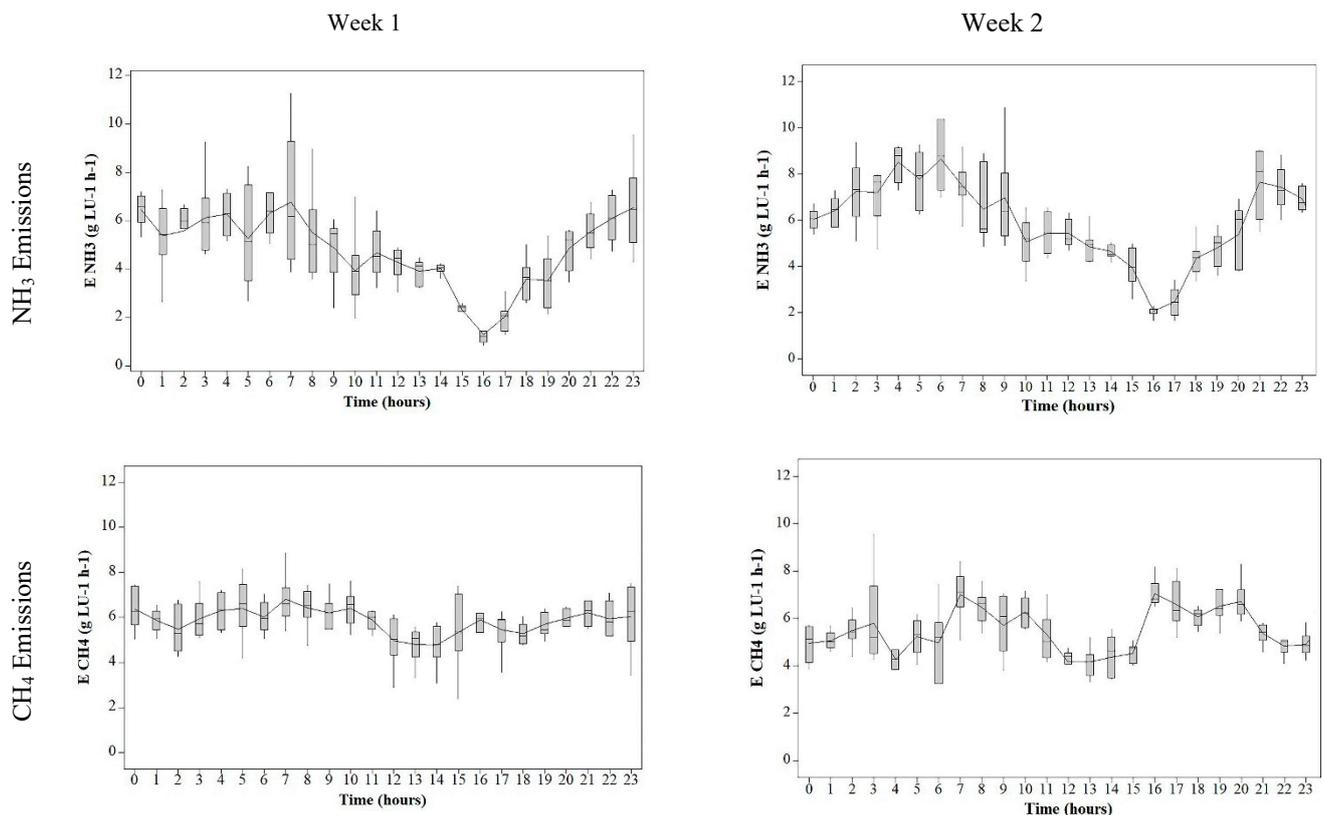


Figure 2. Daily trend of NH₃ and CH₄ emissions during W1 and W2.

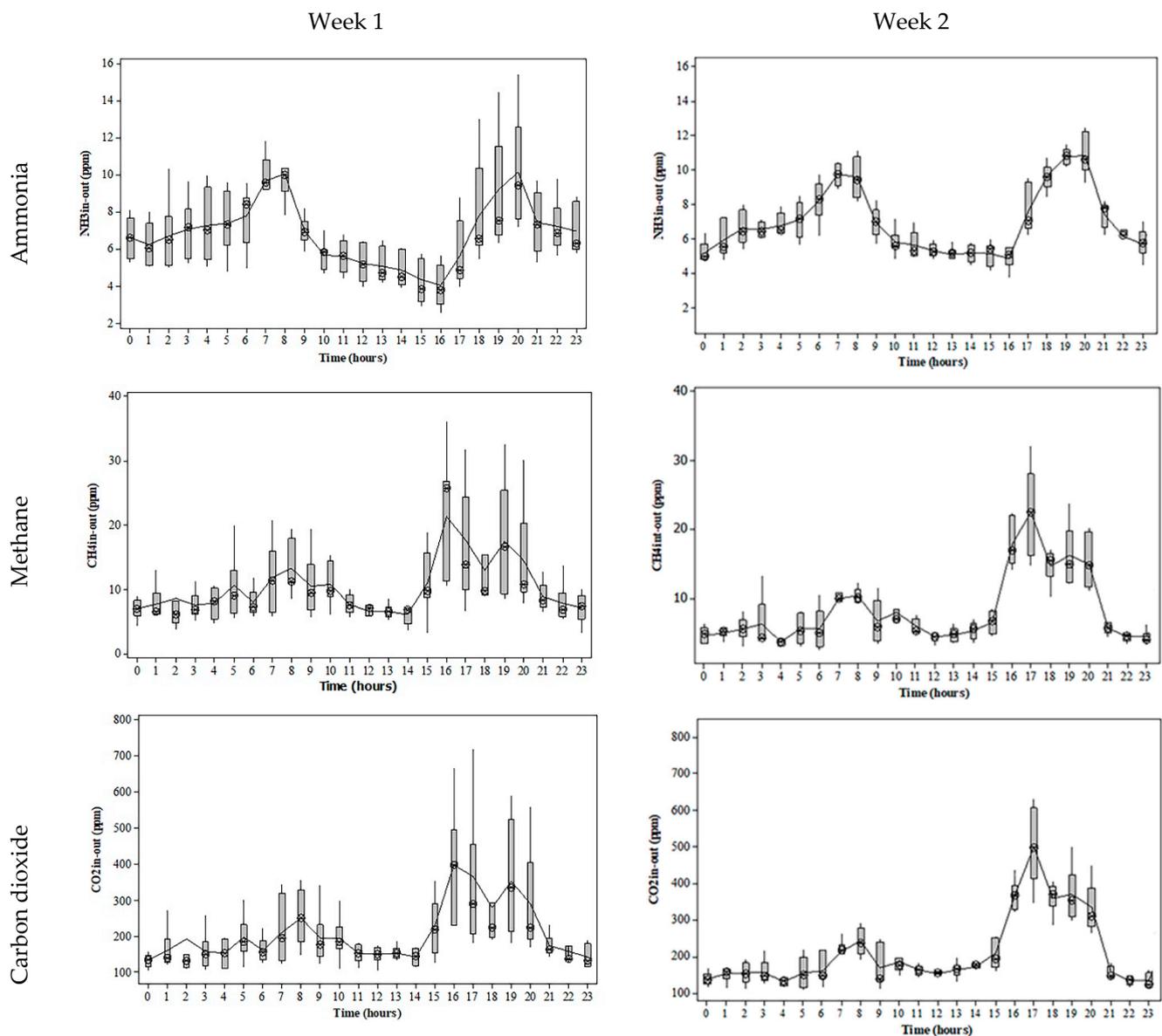


Figure 3. Daily difference between indoor and outdoor gas concentrations of gas pollutants (i.e., NH_3 and CH_4) and tracer gas (i.e., CO_2) during W1 and W2.

3.2. Influence of THI on NH_3 and CH_4 Emissions

The results of the one-way ANOVA (Table 3) showed that groups of NH_3 and CH_4 emissions at different THIs were significantly different for both W1 and W2. In detail, NH_3 emissions at $\text{THI} \leq 72$, $72 < \text{THI} \leq 78$ and $78 < \text{THI} \leq 84$ were all significantly different. The highest NH_3 emissions occurred when the THI was lower than 72, whereas they were lowest at $78 < \text{THI} < 84$. Moreover, it was found a negative correlation between NH_3 emissions and THI ($r = -0.70$ with $p < 0.001$ in W1 and $r = -0.65$ with $p < 0.001$ in W2). These results are strongly related to the cow behaviour and can be explained by analysing the emitting source of the gas. In fact, when the THI was high during the central hours of the day (Table 2), cows were mainly in the lying behaviour in the cubicles where the cooling system was operated. Therefore, the chemical process for NH_3 production was reduced due to the presence of water on the floor [13] and the reduced mixing of urea and faeces performed by cow activity [28]. In addition, for CH_4 , the lowest emissions occurred at $78 < \text{THI} < 84$. The reduction in CH_4 is not related to a direct effect of climatic factors on CH_4 emissions, but to an indirect effect of the animals and their metabolic activity. Besides

the effect of heat stress on cow behaviour reported in the previous section, in the literature, Abeni and Galli [39] found that during heat stress, total rumination time decreased. The reduction in CH₄ could be related to the reduced rumination activity even though it was not proved a direct effect of rumination on CH₄ production [40].

Table 3. Results of statistical analyses for gas emissions at different groups of THI during W1 and W2.

Gas Emissions	p Value	W1			p Value	W2		
		Groups	Mean	SD		Groups	Mean	SD
NH ₃	0.0001	THI ≤ 72	6.18 ^a	1.47	0.0001	THI ≤ 72	7.37 ^a	1.31
		72 < THI ≤ 78	4.37 ^b	1.62		72 < THI ≤ 78	5.94 ^b	1.88
		78 < THI < 84	3.02 ^c	1.21		78 < THI < 84	4.44 ^c	1.39
CH ₄	0.0001	THI ≤ 72	6.19 ^a	1.01	0.001	72 < THI ≤ 78	6.06 ^a	0.96
		72 < THI ≤ 78	5.98 ^a	0.73		THI ≤ 72	5.33 ^b	1.18
		78 < THI < 84	5.11 ^b	1.07		78 < THI < 84	5.23 ^b	1.26

^{a,b,c} Groups of values that do not share a letter (a, b, c) are significantly different.

3.3. Influence of Cow Activity on NH₃ and CH₄ Emissions

The statistical analyses at varying cow behaviour showed a significant difference between groups of gas emissions in both W1 and W2 (Table 4). NH₃ emissions were highest during barn cleaning due to the high NH₃ concentrations during cleaning measured by D'Urso et al. [28] during the same weeks. Moreover, Figure 3 showed that NH_{3in}-NH_{3out} increased during the cleaning of the barn in the early morning, whereas CO_{2in}-CO_{2out} concentrations varied less. Therefore, the ratio between pollutant and tracer gas contributed to enhance NH₃ emissions during floor cleaning; this is in line with other studies [29]. Besides the presence of water on the floor, the lowest NH₃ emissions, obtained during cow activity, were attributed to the dilution and flushing effects of the high air velocities during the central hours of the day (Table 2). The effect of air velocity contributed to reduce CH₄ emissions during cow lying, together with the effect of the frequent cows' sleeping bouts during night hours.

Table 4. Results of statistical analyses for gas emissions at different groups of cow activity during W1 and W2.

Gas Emissions	p Value	W1			p Value	W2		
		Groups	Mean	SD		Groups	Mean	SD
NH ₃	0.0001	cleaning	6.14 ^a	2.36	0.0001	cleaning	6.99 ^a	1.405
		lying	5.40 ^a	1.41		lying	6.37 ^a	1.42
		activity	3.73 ^b	1.82		activity	5.15 ^b	2.29
CH ₄	0.008	cleaning	6.61 ^a	0.97	0.0001	cleaning	6.73 ^a	0.91
		activity	5.85 ^b	0.98		activity	5.96 ^b	1.14
		lying	5.69 ^b	1.01		lying	4.89 ^c	0.93

^{a,b,c} Groups of values that do not share a letter (a, b, c) are significantly different.

4. Conclusions

A study on NH₃ and CH₄ emissions was carried out in an open-sided free-stall barn in a hot Mediterranean climate in order to test the effect of different managements of the cooling system. The aim of providing improved knowledge on the dependence of NH₃ and CH₄ emissions at varying barn managements was achieved in a period of two weeks, characterised by similar microclimatic conditions. Environmental and animal-related parameters were found to have a significant influence on gas emissions ($p < 0.01$) for both NH₃ and CH₄. When the sprinkler system in the feeding alley was not operated, the values of NH₃ emissions increased from 4.73 g LU⁻¹ h⁻¹ in W1 to 5.90 g LU⁻¹ h⁻¹ in W2, and CH₄

emissions were reduced from 5.85 g LU⁻¹ h⁻¹ in W1 to 5.52 g LU⁻¹ h⁻¹ in W2. The effects of changes in the management of the barn can influence microclimatic conditions with the increase or reduction in heat stress for cows. The consequence is the adaptation of the animal behaviour to the different management conditions with the consequent variation in the gas emissions. Under hot climatic conditions, the reduction in gas emissions can derive not only from mitigation strategies, but also from heat stress conditions for the cows. This effect is to be analysed as it could produce negative effects on milk production. In conclusion, this study showed how the management of the cooling system should be supported by a behavioural analysis in order to verify the benefit on the animal and the environment. It is also useful to carry out analyses on daily emissions to provide additional information about how dairy cow activity is affected by the barn management. Further studies regarding the effects of barn management on animal behaviour and emissions per unit of milk produced may provide additional knowledge for the improvement of mitigation strategies aimed at emissions reduction.

Author Contributions: Conceptualization, P.R.D. and C.A.; methodology, P.R.D. and C.A.; software, P.R.D.; validation, P.R.D. and C.A.; formal analysis, P.R.D.; investigation, P.R.D. and C.A.; resources, C.A.; data curation, P.R.D. and C.A.; writing—original draft preparation, P.R.D.; writing—review and editing, C.A. and G.C.; visualization, P.R.D.; supervision, C.A. and G.C.; project administration, C.A.; funding acquisition, C.A. All authors have read and agreed to the published version of the manuscript.

Funding: The research study was funded by the University of Catania through the ‘Piano incentivi per la ricerca di Ateneo 2020–2022-Linea 2’ project on ‘Engineering solutions for sustainable development of agricultural buildings and land—LANDSUS’ (ID: 5A722192152) coordinated by Prof. Claudia Arcidiacono. The INNOVA device was funded by the project “Centro per l’innovazione dei sistemi di qualità tracciabilità e certificazione dell’agroalimentare”—AGRIVET (ID: G46D15000170009).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request due to privacy restrictions.

Acknowledgments: The authors are grateful to the farm ALPA S.S. for providing the opportunity of carrying out the tests. The authors wish to thank the Sicilian Agro-meteorological Information Service (SIAS accessed on 12 May 2021, <http://www.sias.regione.sicilia.it/>) for providing measured weather data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. EEA. European Union Emission Inventory Report 1990–2017 under the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP). In *EEA Technical Report*; EEA: Copenhagen, Denmark, 2019.
2. FAO. Climate change and the global dairy cattle sector. In *The Role of the Dairy Cattle Sector in a Low-Carbon Future*; Global Agenda for Sustainable Livestock: Manhattan, KS, USA, 2019.
3. Janke, D.; Willink, D.; Ammon, C.; Hempel, S.; Schrade, S.; Demeyer, P.; Hartung, E.; Amon, B.; Ogink, N.; Amon, T. Calculation of ventilation rates and ammonia emissions: Comparison of sampling strategies for a naturally ventilated dairy barn. *Biosyst. Eng.* **2020**, *198*, 15–30. [[CrossRef](#)]
4. Hempel, S.; Menz, C.; Pinto, S.; Galán, E.; Janke, D.; Estellés, F.; Müschner-Siemens, T.; Wang, X.; Heinicke, J.; Zhang, G.; et al. Heat stress risk in European dairy cattle husbandry under different climate change scenarios—uncertainties and potential impacts. *Earth Syst. Dyn.* **2019**, *10*, 859–884. [[CrossRef](#)]
5. Ramón-Moragues, A.; Carulla, P.; Mínguez, C.; Villagrà, A.; Estellés, F. Dairy Cows Activity under Heat Stress: A Case Study in Spain. *Animals* **2021**, *11*, 2305. [[CrossRef](#)]
6. Arcidiacono, C. Engineered Solutions for Animal Heat Stress Abatement in Livestock Buildings. 2018. Available online: <https://cigrjournal.org/index.php/Ejournal/article/view/4705> (accessed on 10 August 2021).
7. D’Emilio, A.; Porto, S.M.; Cascone, G.; Bella, M.; Gulino, M. Mitigating heat stress of dairy cows bred in a free-stall barn by sprinkler systems coupled with forced ventilation. *J. Agric. Eng.* **2017**, *48*, 190–195. [[CrossRef](#)]

8. Honig, H.; Miron, J.; Lehrer, H.; Jackoby, S.; Zachut, M.; Zinou, A.; Portnick, Y.; Moallem, U. Performance and welfare of high-yielding dairy cows subjected to 5 or 8 cooling sessions daily under hot and humid climate. *J. Dairy Sci.* **2012**, *95*, 3736–3742. [[CrossRef](#)]
9. Porto, S.M.; D’Emilio, A.; Cascone, G. On the influence of the alternation of two different cooling systems on dairy cow daily activities. *J. Agric. Eng.* **2017**, *48*, 21–27. [[CrossRef](#)]
10. Saha, C.K.; Ammon, C.; Berg, W.; Loebstin, C.; Fiedler, M.; Brunsch, R.; Von Bobrutzki, K. The effect of external wind speed and direction on sampling point concentrations, air change rate and emissions from a naturally ventilated dairy building. *Biosyst. Eng.* **2013**, *114*, 267–278. [[CrossRef](#)]
11. Ngwabie, N.; Jeppsson, K.-H.; Gustafsson, G.; Nimmermark, S. Effects of animal activity and air temperature on methane and ammonia emissions from a naturally ventilated building for dairy cows. *Atmos. Environ.* **2011**, *45*, 6760–6768. [[CrossRef](#)]
12. Poteko, J.; Zähler, M.; Schrade, S. Effects of housing system, floor type and temperature on ammonia and methane emissions from dairy farming: A meta-analysis. *Biosyst. Eng.* **2019**, *182*, 16–28. [[CrossRef](#)]
13. Hempel, S.; Saha, C.K.; Fiedler, M.; Berg, W.; Hansen, C.; Amon, B.; Amon, T. Non-linear temperature dependency of ammonia and methane emissions from a naturally ventilated dairy barn. *Biosyst. Eng.* **2016**, *145*, 10–21. [[CrossRef](#)]
14. Bohmanova, J.; Misztal, I.; Cole, J. Temperature-Humidity Indices as Indicators of Milk Production Losses due to Heat Stress. *J. Dairy Sci.* **2007**, *90*, 1947–1956. [[CrossRef](#)]
15. Hoffmann, G.; Herbut, P.; Pinto, S.; Heinicke, J.; Kuhla, B.; Amon, T. Animal-related, non-invasive indicators for determining heat stress in dairy cows. *Biosyst. Eng.* **2020**, *199*, 83–96. [[CrossRef](#)]
16. Liu, J.; Li, L.; Chen, X.; Lu, Y.; Wang, D. Effects of heat stress on body temperature, milk production, and reproduction in dairy cows: A novel idea for monitoring and evaluation of heat stress—A review. *Asian-Australas. J. Anim. Sci.* **2019**, *32*, 1332–1339. [[CrossRef](#)] [[PubMed](#)]
17. Calegari, F.; Calamari, L.; Frazzi, E. Misting and fan cooling of the rest area in a dairy barn. *Int. J. Biometeorol.* **2011**, *56*, 287–295. [[CrossRef](#)] [[PubMed](#)]
18. Frazzi, E.; Calamari, L.; Calegari, F.; Stefanini, L. Behavior of dairy cows in response to different barn cooling systems. *Trans. ASAE* **2000**, *43*, 387–394. [[CrossRef](#)]
19. Bava, L.; Tamburini, A.; Penati, C.; Riva, E.; Mattachini, G.; Provolo, G.; Sandrucci, A. Effects of feeding frequency and environmental conditions on dry matter intake, milk yield and behaviour of dairy cows milked in conventional or automatic milking systems. *Ital. J. Anim. Sci.* **2012**, *11*, 230–235. [[CrossRef](#)]
20. Provolo, G.; Riva, E. One year study of lying and standing behaviour of dairy cows in a freestall barn in Italy. *J. Agric. Eng.* **2009**, *40*, 27–34. [[CrossRef](#)]
21. ISPRA. Italian Greenhouse Gas Inventory 1990–2019. In *National Inventory Report 2021*; ISPRA: Rome, Italy, 2021.
22. Overton, M.; Sischo, W.; Temple, G.; Moore, D. Using Time-Lapse Video Photography to Assess Dairy Cattle Lying Behavior in a Free-Stall Barn. *J. Dairy Sci.* **2002**, *85*, 2407–2413. [[CrossRef](#)]
23. König, M.; Hempel, S.; Janke, D.; Amon, B.; Amon, T. Variabilities in determining air exchange rates in naturally ventilated dairy buildings using the CO₂ production model. *Biosyst. Eng.* **2018**, *174*, 249–259. [[CrossRef](#)]
24. Ngwabie, N.; Jeppsson, K.-H.; Nimmermark, S.; Swensson, C.; Gustafsson, G. Multi-location measurements of greenhouse gases and emission rates of methane and ammonia from a naturally-ventilated barn for dairy cows. *Biosyst. Eng.* **2009**, *103*, 68–77. [[CrossRef](#)]
25. Ogink, N.; Mosquera, J.; Calvet, S.; Zhang, G. Methods for measuring gas emissions from naturally ventilated livestock buildings: Developments over the last decade and perspectives for improvement. *Biosyst. Eng.* **2013**, *116*, 297–308. [[CrossRef](#)]
26. CIGR. Climatization of animal houses. In *4th Report of Working Group: Heat and Moisture Production at Animal and House Levels*; Pedersen, S., Sallvik, K., Eds.; CIGR: Liege, Belgium, 2002.
27. Hempel, S.; König, M.; Menz, C.; Janke, D.; Amon, B.; Banhazi, T.M.; Estellés, F.; Amon, T. Uncertainty in the measurement of indoor temperature and humidity in naturally ventilated dairy buildings as influenced by measurement technique and data variability. *Biosyst. Eng.* **2018**, *166*, 58–75. [[CrossRef](#)]
28. D’Urso, P.; Arcidiacono, C.; Valenti, F.; Cascone, G. Assessing Influence Factors on Daily Ammonia and Greenhouse Gas Concentrations from an Open-Sided Cubicle Barn in Hot Mediterranean Climate. *Animals* **2021**, *11*, 1400. [[CrossRef](#)]
29. Mazur, K.; Roman, K.; Wardal, W.J.; Borek, K.; Barwicki, J.; Kierończyk, M. Emission of harmful gases from animal production in Poland. *Environ. Monit. Assess.* **2021**, *193*, 1–9. [[CrossRef](#)]
30. Saha, C.; Ammon, C.; Berg, W.; Fiedler, M.; Loebstin, C.; Sanftleben, P.; Brunsch, R.; Amon, T. Seasonal and diel variations of ammonia and methane emissions from a naturally ventilated dairy building and the associated factors influencing emissions. *Sci. Total Environ.* **2014**, *468–469*, 53–62. [[CrossRef](#)] [[PubMed](#)]
31. Mendes, L.B.; Pieters, J.G.; Snoek, D.; Ogink, N.W.M.; Brusselman, E.; Demeyer, P. Reduction of ammonia emissions from dairy cattle cubicle houses via improved management- or design-based strategies: A modeling approach. *Sci. Total Environ.* **2017**, *574*, 520–531. [[CrossRef](#)] [[PubMed](#)]
32. Herbut, P.; Angrecka, S. Relationship between THI level and dairy cows’ behaviour during summer period. *Ital. J. Anim. Sci.* **2017**, *17*, 226–233. [[CrossRef](#)]
33. De Pablo, P.; Tateo, A.; Zezza, F.; Corrente, M.; Centoducati, P. Influence of free-stall flooring on comfort and hygiene of dairy cows during warm climatic conditions. *J. Dairy Sci.* **2006**, *89*, 4583–4595. [[CrossRef](#)]

34. Zetouni, L.; Difford, G.; Lassen, J.; Byskov, M.; Norberg, E.; Løvendahl, P. Is rumination time an indicator of methane production in dairy cows? *J. Dairy Sci.* **2018**, *101*, 11074–11085. [[CrossRef](#)] [[PubMed](#)]
35. Ngwabie, N.M.; VanderZaag, A.; Jayasundara, S.; Wagner-Riddle, C. Measurements of emission factors from a naturally ventilated commercial barn for dairy cows in a cold climate. *Biosyst. Eng.* **2014**, *127*, 103–114. [[CrossRef](#)]
36. Mendes, L.; Edouard, N.; Ogink, N.; Van Dooren, H.J.C.; FerreiraTinôco, I.D.F.; Mosquera, J. Spatial variability of mixing ratios of ammonia and tracer gases in a naturally ventilated dairy cow barn. *Biosyst. Eng.* **2015**, *129*, 360–369. [[CrossRef](#)]
37. Bell, M.; Craigon, J.; Saunders, N.; Goodman, J.R.; Garnsworthy, P. Does the diurnal pattern of enteric methane emissions from dairy cows change over time? *Animals* **2018**, *12*, 2065–2070. [[CrossRef](#)] [[PubMed](#)]
38. D’Urso, P.R.; Arcidiacono, C. Effect of the Milking Frequency on the Concentrations of Ammonia and Greenhouse Gases within an Open Dairy Barn in Hot Climate Conditions. *Sustainability* **2021**, *13*, 9235. [[CrossRef](#)]
39. Abeni, F.; Galli, A. Monitoring cow activity and rumination time for an early detection of heat stress in dairy cow. *Int. J. Biometeorol.* **2017**, *61*, 417–425. [[CrossRef](#)]
40. Beauchemin, K. Invited review: Current perspectives on eating and rumination activity in dairy cows. *J. Dairy Sci.* **2018**, *101*, 4762–4784. [[CrossRef](#)] [[PubMed](#)]