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Research Paper

Effects of environmental and housing system factors on ammonia and greenhouse gas emissions from cattle barns: A meta-analysis of a global data collation

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A R T I C L E I N F O

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A B S T R A C T

This study provides a meta-analysis on the relationships between cattle barn CH_4, NH_3 and N_2O emission rates and their key drivers (i.e., housing type, floor type, environmental conditions). Understanding these relationships is essential to reduce uncertainties in emission inventories and suggest targeted mitigation measures. The total number of daily emission rates included in the analysis was 139 for CH_4, 293 for NH_3 and 100 for N_2O emissions. Emission rates in the database showed a large variation with 45–803.5 g/LU d^{-1} for CH_4, 0.036–146.7 gN LU^{-1} d^{-1} for NH_3, and 0.002–18 gN LU^{-1} d^{-1} for N_2O emissions. Despite the high emission variability, significant effects were identified·NH_3 showed positive correlation with air temperature; NH_3 emissions differed between housing types but not between floor types·NH_3 emissions from tied stalls were lower than the ones from cubicle housing regardless of the floor type. Additionally, NH_3 emissions from loose housings were lower than the ones from cubicle housing·NH_3 and N_2O emission rates from temperate wet zones were lower than the ones from temperate dry zones. CH_4 emission rates were affected by environmental factors only and not by housing and floor type, showing negative correlation with air temperature and humidity. The factors investigated can be suggested as ancillary variables and descriptors when cattle barn emissions are measured, in order to make best use of emission data. Country-specific data of these key drivers can be included into national inventories to adapt them to different agroecosystems and support targeted policies.

1. Introduction

Countries are under pressure to tackle climate change and committed to greenhouse gas (GHG) emissions reduction targets under the Kyoto Protocol in the short and in the long term (UNFCCC, 2020). According to the IPCC Sixth Assessment Report, global GHG emissions should be reduced by 43 % by 2030 to limit global warming to 1.5 °C, aligning with the aims of the Paris Agreement (Shukla et al., 2022; UNFCCC, 2015). In particular, the need to quickly reduce global CH_4 emissions to slow warming and "buy time" is highlighted (Ming et al., 2022). Therefore, at the UN Climate Change Conference (COP 26) held in Glasgow in November 2021, 105 countries representing 45 % of global CH_4 emissions signed "The Global Methane Pledge", committing to reduce anthropogenic CH_4 emissions across all sectors by 30 % below 2020 levels by 2030.

Almost a quarter of the global anthropogenic GHG emissions are attributed to Agriculture, Forestry, and Other Land Use (AFOLU) (Shukla et al., 2022), where the contribution of the livestock sector to global GHG emissions is undeniably significant (Grossi et al., 2019). In particular, agriculture is considered one of the main sources of CH_4 and

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N_2O, two high warming potential gases. Animal production produces roughly 37 % and 65 % of global emissions of CH_4 and N_2O, respectively (Steinfeld and Wassenaar, 2007). Emissions from enteric fermentation, livestock manure left on pastures and applied to cropland, and manure management systems constitute respectively 39 %, 20 % and 6 % of total non-CO_2 GHG emissions from agriculture (FAO, 2020). For the European Union, the first three largest sources of agricultural GHG emissions are enteric fermentation (44.7 %), direct nitrous oxide (N_2O) emissions from soil (30.8 %) and manure management (14.6 %) (EEA, 2020). Therefore, emission mitigation from the livestock sector is essential to reach the required emission reductions. The climate law in Europe aims to achieve climate neutrality of the AFOLU sector by 2035 (European Commission, 2021). Besides GHG emissions reduction targets, the European Union set stringent targets to reduce ammonia (NH_3) emissions with the NEC Directive 2016/2284/EU (EEA, 2019), since NH_3 is a pollutant indirectly responsible for N_2O emissions. Agriculture is responsible for around 81 % of NH_3 emissions globally (Wyer et al., 2022); 40–49 % of NH_3 emissions come from manure storage and animal housing (Cai et al., 2021). Emissions from manure management include emissions from livestock housing, manure handling and storage, grazing and manure application to soils. Different management and environmental factors in livestock housing affect the release of gaseous emissions from livestock manure. Barn emissions of NH_3 occur from the hydrolysis of urea by the urease enzyme when feces and urine are excreted on the barn floor (Bougouin et al., 2016; Amon et al., 2021a). NH_3 formation depends on the equilibrium between NH_3 and ammonium (NH_4^+). Under high pH conditions, the equilibrium shifts towards NH_3 release. Additionally, the equilibrium is highly dependent on the Henry's constant, which exponentially increases with temperature and results in an increase in NH_3 release (Amon et al., 2021a). The release of N_2O depends on the nitrification and denitrification processes, which are mainly driven by presence and absence of oxygen (Tang et al., 2019). Ammonia is oxidized under aerobic conditions to nitrite and nitrate, while denitrification reduces nitrate to N_2O under oxygen deficit environment (Petersen and Sommer, 2011; Sommer et al., 2013; Amon et al., 2021a). NH_3 and N_2O emissions are clearly intertwined, as they are both part of the N pathway along the manure management chain, from excretion to field use. Studies from Hou et al. (2015), Emmerling et al. (2020) and Kavanagh et al. (2021) reported that reducing the manure concentration of free ammonia (e.g., by means of acidification) and total ammonia (e.g., by means of crude protein reduction in the diet) can simultaneously reduce the emission of N_2O and NH_3, while other strategies can reduce the emissions of one of the two while increasing the other. On the other hand, CH_4 is produced by the breakdown of organic carbon in anaerobic conditions. The four stages of anaerobic breakdown (hydrolysis, acidogenesis, acetogenesis and methanogesis) are affected by various factors such as pH, temperature, volatile fatty acids, and C/N ratio (Amon, 1998).

Many studies reported NH_3 and CH_4 emission measurements from cattle barns under different management and environmental conditions (Ngwabie et al., 2011, Leytem et al., 2011; Kumari et al., 2020). Results of these studies vary in relation to the different environmental and housing conditions, animal performance, diet composition and climate. Therefore, there is a wide range of NH_3 and GHG emissions reported from cattle housing. Recently, some comparative studies conducted meta-analyses on published livestock emissions data, focusing on the relationship between emissions from manure management and environmental and management factors. In a meta-analysis, Bougouin et al. (2016) looked at nutritional and environmental effects on NH_3 emissions from dairy cattle housing. They found that NH_3 emissions are driven by a variety of factors such as housing system, season and animal diet, but the literature considered did not sufficiently describe diet and animal-related variables, which limited their analysis. Sajeev et al. (2017) investigated the relationship between dietary manipulation and NH_3 emissions from cattle and pig manure. They conducted a meta-analysis to quantify the effects of NH_3 abatement in relation to animal diets to help develop refined emission factors and confirmed that NH_3 emissions and diet crude protein level are strongly related. Most of the literature considered dairy cattle rather than beef cattle housings. Sanchis et al. (2019) studied the effect of temperature, wind speed, relative humidity and ventilation rate on NH_3 emissions from dairy cattle housing by analyzing the data published in peer reviewed publications. Poteko et al. (2019) and Qu et al. (2021) analyzed the effects of housing systems, floor types and different environmental factors on CH_4 and NH_3 emissions from dairy barns. The study of Qu et al. (2021) was based on the largest number of observations, 55 and 100 for CH_4 and NH_3 respectively. Both studies concluded that emissions from solid floors do not substantially differ from emissions from perforated (i.e. slatted) floors, while environmental factors have a clear effect on gaseous emissions. However, they pointed out that the differences in farm conditions, measurement methods and data availability represent significant challenges in demonstrating the effects of key factors on emissions. They all reported that the effect of climate on NH_3 emissions should be studied more in detail, aiming to establish relationships between emissions and specific climate zones, since temperature and seasonal variations are prominent factors for NH_3 emissions. Van der Weerden et al. (2020) studied the relationship of N_2O emission factors with livestock type, excreta type and slope class for ruminants in New Zealand, contributing to improve the accuracy of emission estimations in emission inventory reporting of the country.

All these studies emphasize the importance of detailed understanding of GHG and NH_3 emissions for emissions reporting and mitigation. They also concluded that data unavailability and variation of emission measurements hindered the analysis and detailed data are needed to establish significant relationships between environmental factors, housing systems and gaseous emissions. This would help to explain the variations in emission rates and increase the accuracy of emission models. Moreover, detailed knowledge on key influencing factors and accurate emission factors reflecting operational and practical conditions are essential for accurate emission reporting since moving from IPCC Tier 1 to Tier 2 and 3 methodologies requires country specific information and high-resolution activity data (Amon et al., 2021b). The study by Baldini et al. (2018) emphasizes the importance of gathering more experimental data to determine emissions factors that accurately estimate emissions from the manure management chain, so that the national inventories can better describe the actual level of emissions. In particular, Hassouna et al. (2010) suggested the necessity for further N_2O emission measurements for dairy cattle houses, which are indeed scarcer than for CH_4 and NH_3.

Cattle housings are important components of the manure management chain. Understanding the variation of emission rates from cattle housings under different conditions can help to develop appropriate emission factors for inventory reporting and support the development and the inventorying of emission mitigation options. The aim of this study is to improve the existing knowledge and to reduce the uncertainty on the effects of key factors, such as housing type, floor type, air temperature, relative humidity, climate zone and animal category (i.e., dairy *vs* beef cattle), on CH_4, NH_3 and N_2O emission rates from cattle housings by means of a meta-analysis. In detail, published NH_3 and GHG emission rates from cattle housing systems collated in the DATAMAN database were analyzed. DATAMAN (https://www.dataman.co.nz) is a global database of GHG and NH_3 emissions from the manure management chain, which has global scope and was compiled and quality controlled by an international team of experts, including data on their influencing factors (Beltran et al., 2021; Hassouna et al., 2023; van der Weerden et al., 2021). Since its geographical coverage was recently expanded by the MELS project (2019–2023, http://www.mels-project.eu), the DATAMAN database provides access to the largest amount of literature data currently available on gaseous emission from manure management and ancillary variables. The DATAMAN housing emissions database includes 269 publications in total, with almost 300 NH_3 and more than 100 CH_4 and N_2O emission observations from dairy and beef cattle. To date, no analysis of such depth and global coverage of cattle barn emissions data has been conducted.

2. Materials and methods

2.1. Dataset description

The DATAMAN database is a global database of GHG and NH_3 emissions from manure management, including key variables affecting emissions from livestock housing, manure storage and field application. Hassouna et al. (2023) described the housing and storage section of the DATAMAN database and the data collation procedure in detail. Briefly, the data were obtained from a web search of published peer-reviewed articles and grey literature (e.g., technical reports, theses and conference papers) whose publication date was not older than 1990. The search was performed using terms relevant to emissions from manure management. For NH_3 and GHG emissions from animal housing, the following acceptance criteria were adopted: i) laboratory, pilot or commercial scale studies only, modelling studies excluded; ii) tracer gas, micrometeorological methods, dynamic enclosure, static enclosure methods accepted; iii) measurements conducted for 6 days or more.

A cattle housing emission dataset was built for this study as a subset of the DATAMAN database, by filtering observations from studies related to dairy and beef cattle barns. The observations included in this dataset originated from studies carried out in real-scale commercial barns or aimed at studying conditions to be replicated in commercial barns. The cattle housing dataset covered a wide range of countries, including 10 EU countries, the United States, Canada, China and the United Kingdom. Four different approaches were adopted to control the quality of the entries: (a) for numeric variables, value ranges were defined basing on experts' judgement, in order to provide an easy first-step mean of quality control; (b) graphical visualizations made possible to identify outliers, which were then checked against the original studies to verify their validity; (c) consistency regarding the attribution of categorical variables (i.e. climate zone, animal category, housing type, floor type) was checked; (d) the dataset was checked for duplication of observations.

This dataset went through a process to harmonize the units of measure of the emission rates reported in the considered studies according to the methodology suggested by Webb et al. (2021). After this process, the emission rates were reported in g N/LU d^{-1} for N_2O and NH_3 emissions and g CH_4 LU^{-1} d^{-1} for CH_4 emissions, where "LU" stands for "livestock units" (i.e. 500 kg of animal live weight), and they were divided into three categories: supplied, derived and estimated rates. Supplied emission rates were directly obtained from the literature without any further calculation. Derived emission rates were converted to the target measure unit using data from the related publication, while estimated emission rates were calculated using external default data (Webb et al., 2021). This was required when the related studies did not report all the data needed to calculate emission rates per livestock unit. Then, the dataset was filtered for the key factors investigated: housing temperature, relative humidity, floor type, housing type, climate zone and animal category (i.e., dairy *vs* beef cattle). The selected observations could be clearly referred to specific climate zones and were obtained from publications reporting information on both housing type and floor type. Most of the observations originated from the EU (148 for NH_3, 98 for CH_4 and 57 for N_2O), followed by the United States (68 for NH_3, 32 for CH_4 and 37 for N_2O). Figures on the number of emission rates by country can be found in the Appendix. Methane emission rates from cattle housing consisted of 139 observations from 41 publications. Out of 139 observations, 124 were originated from 35 publications reporting barn temperature, and 83 observations came from 19 publications reporting also relative humidity. The NH_3 dataset (n = 293) included observations from 85 publications. Out of 293 observations, 182 were originated from 64 publications reporting barn temperature, of which 26 publications (n = 87) reported also relative humidity. The N_2O dataset (n = 100) included observations from 37 publications, of which 32 recorded temperature (n = 80), and 17 reported also relative humidity (n = 43).

2.2. Key factors

The key factors considered in this study were 4 categorical variables (housing type, floor type, animal category and climate zone) and 2 continuous variables (barn temperature and relative humidity). The housing type variable was divided into 4 subcategories: i) cubicle housing, ii) loose housing (i.e., deep litter), iii) tied stalls and iv) feedlot. These subcategories were based on the RAMIRAN Glossary of terms on manure management (Pain and Menzi, 2011). This glossary defines cubicle housings as "buildings divided into rows of individual stalls or cubicles in which animals lay when at rest but are not restrained", in which "a small amount of bedding is placed in each cubicle". Loose housings are housings where "animals have free access over the whole area of the building or pen", commonly with "a deep layer of bedding (usually straw) to be spread over the floor that is removed from the building, typically once or twice per winter, as farmyard manure". Tied stalls are housings "in which livestock are permanently restrained in a stall whilst they are kept in the house and so have restricted freedom of movement". Feedlots are "concentrated, confined livestock operation outdoor areas wherein the livestock are fed at the place of confinement and crop production is not sustained".

The floor type variable was divided into 3 subcategories: i) solid, ii) slatted and iii) earthen. According to the RAMIRAN Glossary, solid floor is "the floor of a building normally constructed of a hard, impermeable material such as concrete", while slatted floor is "a metal, concrete or plastic floor with slots that allow feces and urine from livestock to drop into a channel or pit beneath." In the considered literature, "earthen floor" is a floor without any coverage.

The "climate zone" factor had 2 levels: i) temperate wet and ii) temperate dry. The dataset observations belong to the temperate domain only and were assigned to one of the "temperate wet" or to the "temperate dry" zone on the basis of the ratio between average annual precipitation and potential evapotranspiration of the study site (wet zones > 1; dry zones < 1) (Beltran et al., 2021).

The number of considered emission rates for each categorical variable and each subcategory is reported in Table 1. For CH_4 emission rates, seven different housing and floor type combinations were observed in the dataset: i) cubicle housings with slatted floor, ii) cubicle housings with solid floor, iii) deep litter with earthen floor, iv) deep litter with solid floor, v) feedlots with earthen floor, vi) tied stalls with slatted floor and vii) tied stalls with solid floor. For NH_3 emission rates, there were eight different combinations, namely: cubicle housings with solid or slatted floor, feedlots with earthen or solid floor, deep litter with earthen or solid floor and tied stalls with slatted or solid floor. For N_2O emission rates, observations were available for seven combinations: cubicle housings with solid or slatted floor, feedlots with earthen floor, deep litter with earthen or solid floor, and tied stalls with slatted or solid floor.

2.3. Statistical analysis

The statistical analysis was performed using the R statistical software (version 4.1.3). The distributions of NH_3 and N_2O emission rates were right skewed, while CH_4 emission rates were normally distributed. Therefore, NH_3 and N_2O emission rates did not fit into a normal distribution and were log transformed for the analysis. As a preliminary check, the effect of the emission rate categories (i.e., supplied, derived, estimated) on the emissions of different housing systems was tested by ANOVA, in order to verify that no significant differences could be attributed to these categories. To this end, the emission rate categories were nested within the housing systems. No significant effect of the emission rate category was observed for CH_4 and N_2O emissions, while the effect of the emission rate category within housing types was significant for NH_3 emissions ($p < 0.0001$). However, the observed

Table 1
Number of observations of CH_4, NH_3 and N_2O emission rates for the key factors analyzed.

	Housing Type				Floor Type			Climate Zone		Animal category	
	Cubicle	Loose	Tied stalls	Feedlot	Earthen	Slatted	Solid	Temperate wet	Temperate dry	Dairy cattle	Beef cattle
CH_4	85	28	15	11	15	49	75	125	14	129	10
NH_3	137	58	69	29	17	102	174	277	16	224	69
N_2O	44	22	24	11	15	31	55	88	13	92	8

differences were related to feedlots only, as feedlot NH_3 emission rates belonged to the "estimated" category only and were significantly higher than those of other housing systems. No significant differences between emission rate categories were found within cubicle housings, loose housings and tied stalls. Thus, supplied, derived and estimated rates were pooled for the subsequent analyses.

The effect of key factors on emission rates was assessed by mixed effects linear models (*lme4* package)(Bates, 2010), considering housing factors (i.e., housing and floor type), climate zone, animal category (i.e., dairy *vs* beef cattle), barn temperature and relative humidity as fixed effects and the experiment of origin (i.e., experiment ID) as random effect. Data availability was restricted by the continuous variables, as barn temperature and relative humidity were not reported for each data point. Therefore, we conducted the analysis by grouping the data according to amount of data available in the key categories. Typically, temperature and relative humidity data lacked for the "temperate dry" zone. For this reason, we looked at the data in two groups to be analyzed separately. In the first group of data, we looked at the effects of the climate zone combined with other categorical variables. The second group of data was made up by observations where temperature and relative humidity were reported, analyzed in combination with categorical variables other than the climate zone. The significances of fixed and random effects were tested by ANOVA (Type III analysis of variance). Fixed effects for each model were tested stepwise and final models were selected according to the significance of each fixed effect. No significant interactions were found, so simple additive models were adopted. The pairwise comparison of levels for categorical fixed effects were assessed by the *predictmeans* package (Luo et al., 2020). The models adopted for each emission type are described below and summarized in Table 2.

CH_4 emission rate models

Model 1: Climate zone and animal category as fixed effects and experiment ID as random effect.

Model 2: Temperature, relative humidity, floor type nested within housing type as fixed effects, experiment ID as random effect.

NH_3 emission rate models

Model 3: Climate zone as fixed effect and experiment ID as random effect.

Model 4: Temperature, floor type nested within housing type as fixed effects, experiment ID as random effect.

N_2O emission rate model

Model 5: Climate zone, animal category and floor type nested within housing type as fixed effects and experiment ID as random effect.

3. Results and discussion

The descriptive statistics of emission rates, temperature and relative humidity measurements of each gas are presented in Table 3. Descriptive statistics show a high variability in emission rates where NH_3, CH_4 and N_2O recorded emissions were between 0.036 to 146.74 g NH_3 LU^{-1} d^{-1}, 44.93 to 803.52 g CH_4 LU^{-1} d^{-1} and 0.002 to 17.98 g N_2O LU^{-1} d^{-1} respectively. In the cattle barn emission dataset, temperatures varied between −1 and 34 °C and relative humidity ranged between 46.5 and 94.6 %. The variability in the data can be related to the wide range of geographical, climate, feeding and animal housing conditions, but also different survey concepts between the various studies and experiments (Qu et al., 2021). Some emissions constitutively show large variations, and this can be related to their right-skewed distribution. For instance, N_2O emission observations from a wide range of environments typically yield data that are highly skewed to the right. These skewed distributions occur because of the complex series of individual processes that interact to produce N_2O with multiplicative effects – i.e., a variable that is defined as the product of a number of elementary variables tends to have a "patchy" spatial distribution (i.e. show "hotspots" where emission is unusually high) and to be skewed to the right (Pennock et al., 2006). Distributions of the emission rates are shown in Fig. 1 of the Supplementary Material. Figs. 1–3 show the distribution of emission rates of CH_4, NH_3 and N_2O for housing and floor systems in the database.

3.1. CH_4 emissions

Fig. 4 shows results of the regression models for temperature and relative humidity. The regression showed an inverse relationship between CH_4 emission rate and temperature ($p = 0.00218$, $n = 83$) and relative humidity ($p = 0.0261$, $n = 83$). The significance of all fixed effects is reported in Table 4.

Enteric fermentation and emissions from manure are the two sources of CH_4 emissions from livestock housing, where enteric fermentation typically contributes 50–80 % CH_4 emissions from the barn (Ngwabie et al., 2014). Therefore, CH_4 emission measurements recorded in the housing dataset can be mostly attributed to rumen activity in cattle and should not be directly affected by housing factors. As shown by previous studies, emissions from enteric fermentation depend on other factors such as seasonal variations, animal activity, feeding strategies, animal diet and barn ventilation (Saha et al., 2014; Sajeev et al., 2017; Jungbluth et al., 2001; Rong et al., 2014), while CH_4 emissions from barn manure are mainly dependent on manure removal practices (Baldini et al., 2016). While studies on emissions from outside storage typically

Table 2
NH_3 and GHG emission models description.

Models description		Variable type	Model1 (CH_4)	Model2 (CH_4)	Model3 (NH_3)	Model4 (NH_3)	Model5 (N_2O)
Fixed effects	Climate Zone	Categorical	✓		✓		✓
	Animal category	Categorical	✓				✓
	Temperature	Numerical		✓		✓	
	Relative humidity	Numerical		✓			
	Floor type nested within housing type	Categorical		✓		✓	✓
Random effects	Experiment ID	Categorical	✓	✓	✓	✓	✓
Number of observations			139	83	293	182	100

Check sign indicates that the model includes the variable in the row.

Table 3
Descriptive statistics of emission rates, temperature and relative humidity.

		Min.	Median	Mean	Max.	1st Quantile	3rd Quantile	Std. dev.	n
CH_4	Emission rate (g CH_4 LU^{-1} d^{-1})	44.93	300	320.2	803.52	249.84	358.3	142.75	139
	Temperature(°C)	1	15.2	14.9	27.6	10.63	19	6.05	127
	Relative humidity (%)	46.5	72	71.2	94.6	63.2	76.95	12.83	83
NH_3	Emission rate (g NH_3 LU^{-1} d^{-1})	0.036	19.76	26.88	146.74	9.3	31.2	27.26	293
	Temperature (°C)	−1	12.5	13.85	34	9.42	18	6.74	182
	Relative humidity (%)	46.5	72	71.49	94.6	61.9	80.55	12.11	87
N_2O	Emission rate (g N_2O LU^{-1} d^{-1})	0.002	1.03	2.33	17.98	0.22	2.95	3.42	101
	Temperature (°C)	2	12.5	13.95	27.6	9.08	19	5.87	80
	Relative humidity (%)	46.5	71.9	69.7	94.6	59.35	81.15	14.42	43

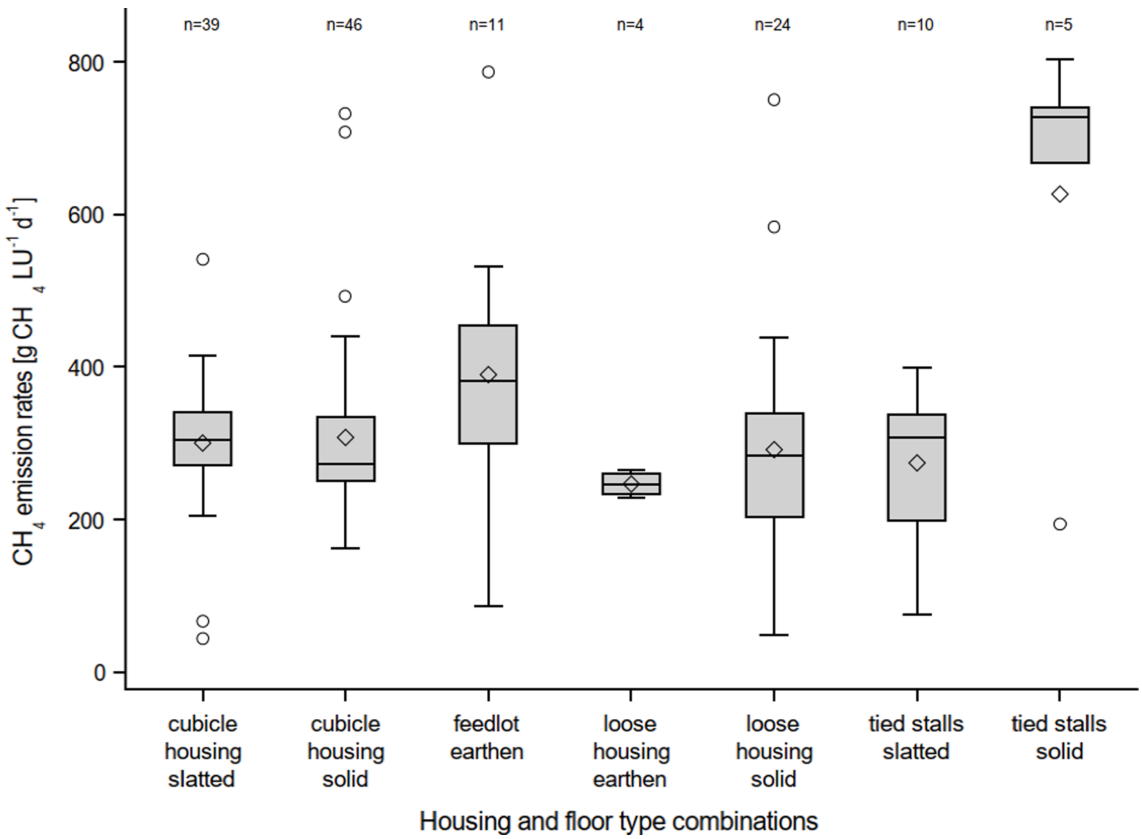

Fig. 1. Distribution of CH_4 emission rates for different housing and floor systems.

reveal an increase in CH_4 emissions with increasing temperatures (Cárdenas et al., 2021; Baral et al., 2018; Amon et al., 2006; Kupper et al., 2020), studies conducted inside dairy barns typically show a negative relationship between temperature and CH_4 emissions, as observed in our analysis. Ngwabie et al. (2014) revealed a pattern that CH_4 emissions were positively correlated with animal activity, where animal activity decreases with increasing temperature. High temperature causes heat stress on animals, causing their digestive activity and defecating frequency to decrease, eventually resulting in lower CH_4 emissions release. Yadav et al. (2016) also supported these findings, showing that heat stress significantly affects digestibility and CH_4 emissions release. Hempel et al. (2020) measured CH_4 emission rates from two cattle housing buildings and revealed clear trends of emissions for different temperature ranges; CH_4 emissions showed an increasing trend when the temperature decreased from 10 °C, while CH_4 emissions did not increase when the temperature was raised above 10 °C. Some studies carried out in temperate-humid areas have shown an increase in methane emissions from cattle barns in the summer season, but attributed this to the manure present in the barn or even to an increased presence of unremoved manure, rather than enteric fermentation (Mathot et al., 2012; Vechi et al., 2022). The meta-analyses of Poteko et al (2019) and Qu et al. (2021) showed opposite trends (i.e. CH_4 emissions positively correlated to temperature), but most of their observations fall within the optimal thermal range of dairy cows, and only a few are related to temperatures higher than 20 °C.

The analysis of the previous literature shows that the effect of relative humidity on CH_4 emission rates has not been studied so far in depth and needs further investigation. Qu et al. (2021) did not detect any relationship between CH_4 emission rates and relative humidity while emphasizing that they had limited relative humidity data. Saha et al. (2014) measured daily and seasonal temperature and relative humidity changes in the barn and identified an effect of relative humidity on CH_4 emissions, as it may affect animal activity.

The animal category and the climate zones did not show significant effects on CH_4 emission rates, although the difference between dairy and beef cattle approached significance (p = 0.07). In addition, no significant differences in barn CH_4 emissions were observed among the considered housing and floor type combinations. Some recent studies support these results. For instance, the analysis by Qu et al. (2021) observed no difference between CH_4 emission rates from solid floor and

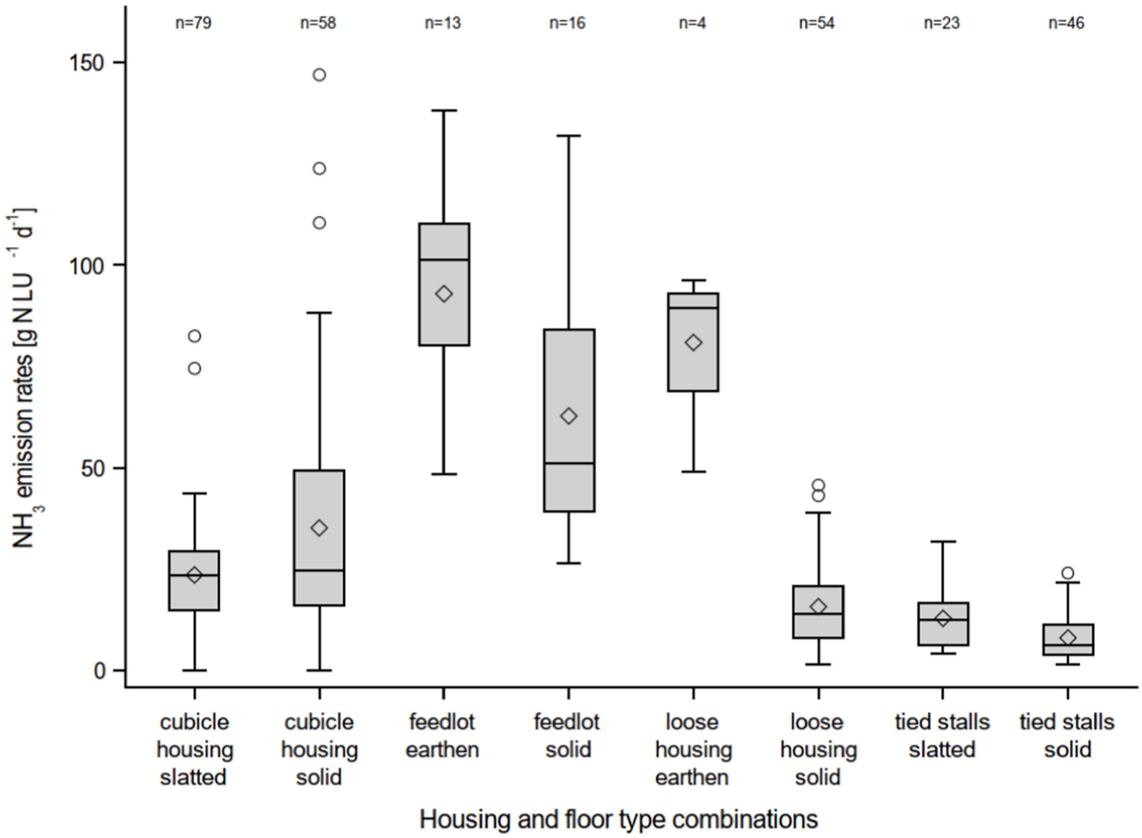

Fig. 2. Distribution of NH_3 emission rates for different housing and floor systems.

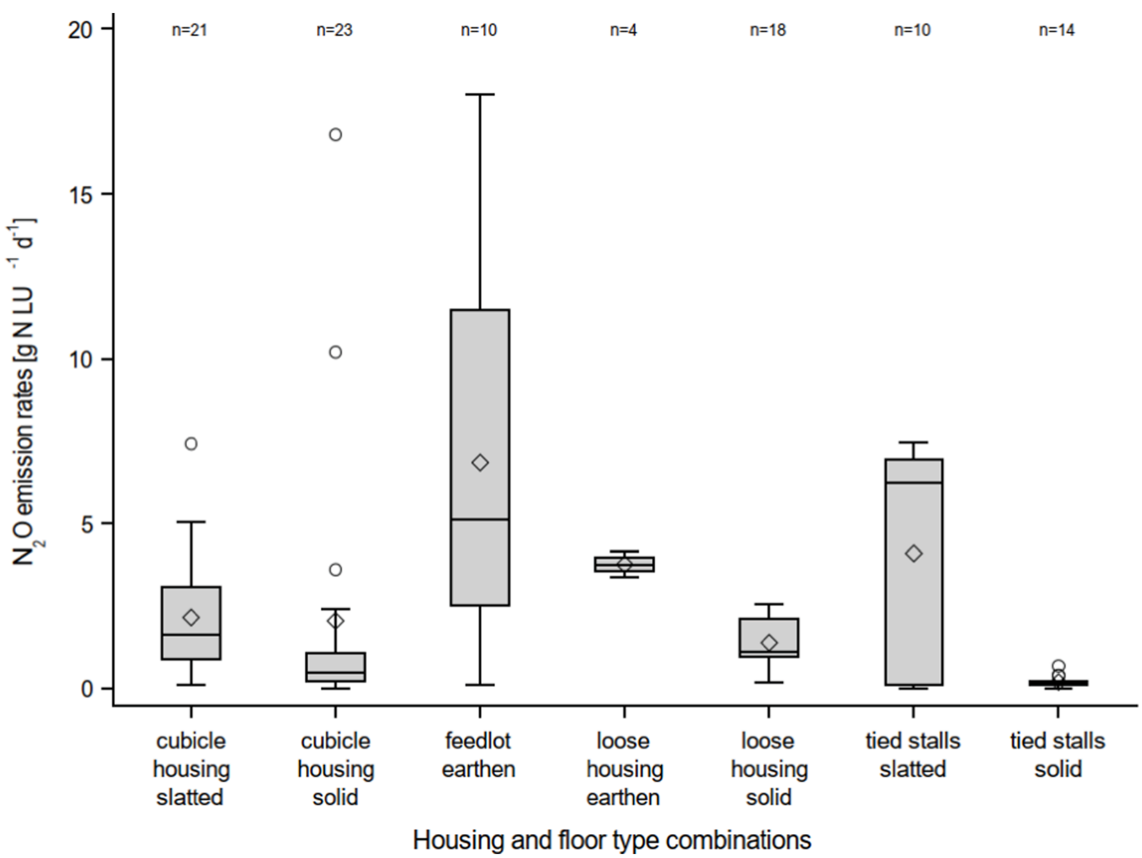

Fig. 3. Distribution of N_2O emission rates for different housing and floor systems.

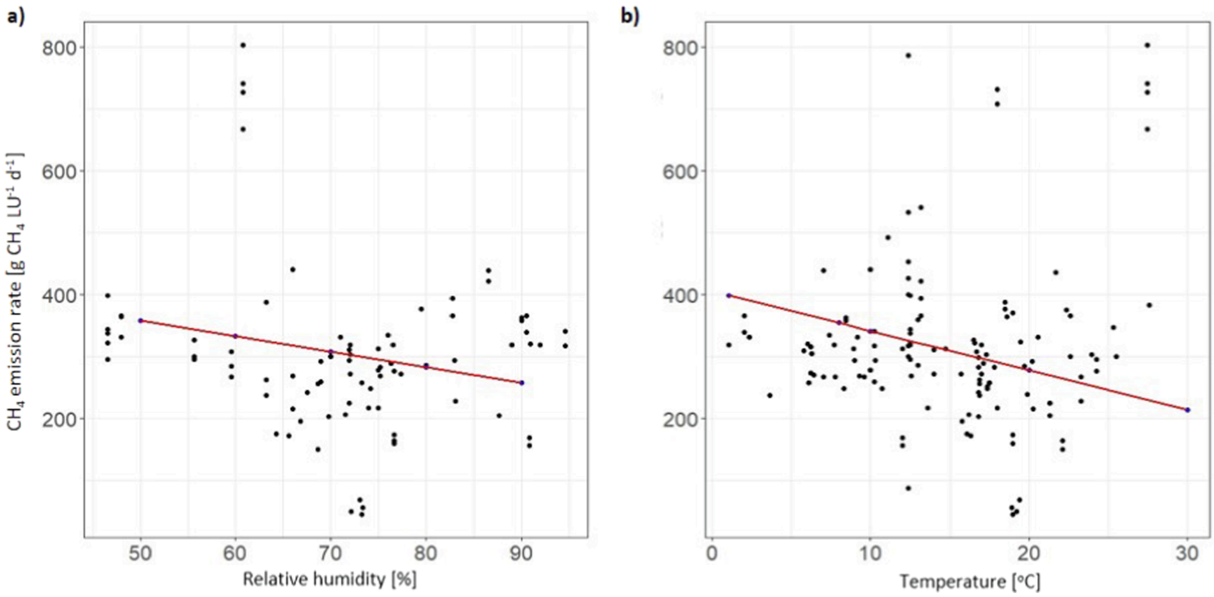

Fig. 4. Regression of CH_4 emission rates over relative humidity (a) and indoor barn temperature (b).

Table 4
Significance of fixed effects based on the ANOVA test ($p < 0.05$).

Emission models	Models	Fixed effects	p value
CH_4	Model 1	Climate zone	0.5772
		Animal category	0.0722
	Model2	Temperature	0.0022
		Relative humidity	0.0261
		Floor type nested with housing type	0.1430
NH_3	Model 3	Climate zone	7.975e−08
	Model 4	Temperature	2.339e−05
		Floor type nested with housing type	3.163e−13
N_2O	Model 5	Climate zone	0.0133
		Floor type nested with housing type	0.0021
		Animal category	0.0189

slatted floor, and similar results were obtained by Pereira et al. (2012). Although Poteko et al. (2019) reported a difference between CH_4 emissions from tied housing and loose housing systems, they acknowledged that their analysis on tied housing depends on very limited data from two studies only. Therefore, this finding requires further investigation. CH_4 emissions from slatted floor housing are rather dependent on the manure storage duration in the pit under the slatted floor. Previous studies found that decreased manure removal frequency from the pits favors anaerobic fermentation, resulting in increased CH_4 emissions (Baldini et al., 2016; Ngwabie et al., 2011).

3.2. NH_3 emissions

Relative humidity and animal category were excluded from the models because no significant relationship with NH_3 emissions was observed in any of the tested models (Table 4). This result is in agreement with Sanchis et al. (2019), who also studied the effect of relative humidity on NH_3 emissions from dairy cattle barns ($n = 43$) and did not report a significant relationship. They attributed this result to the high variability of measured relative humidity values in the barn. Similarly, in our study the collated relative humidity data showed a wide range (46–95 %, $n = 83$). Moreover, all relative humidity measurements recorded in the dataset belong to temperate wet zones and relative humidity data are unavailable for temperate dry zones. Nonetheless, temperate wet and temperate dry climate zones reflect different humidity conditions, and differences in NH_3 emissions between climate zones were observed. In fact, testing the effect of climate zones in a single effect model over the entire data set showed that climate zone is a significant predictor of NH_3 emissions. Emission rates from temperate wet zones were much lower than from temperate dry zones. The measurements of Feng et al. (2022) showed a negative correlation between humidity and NH_3 emissions. Other studies also emphasized the impact of climate conditions together with different housing and management factors (Philippe et al., 2011; Saha et al., 2014; Qu et al., 2021). Climate zones have recently become of interest when determining emission factors, as they are a surrogate for a number of other variables that have been shown to affect the emission factors. The IPCC (2019) highlights the importance of considering climate zones when estimating emissions from manure management systems, since temperature and humidity have a strong influence on NH_3 emissions. Theoretically, indoor relative humidity should have an effect on emissions too, but we did not observe it because of the lack of relative humidity data for temperate dry climate zones.

The analysis showed that temperature is a highly significant predictor of NH_3 emissions ($p < 0.001$). A significant linear relationship was observed between NH_3 emissions and indoor temperature as shown in Fig. 5. The regression model resulted in 0.037 g NH_3LU^{-1} d^{-1} increase in NH_3 emissions when temperature increased 1 °C. Other studies relating indoor housing temperature with NH_3 emissions observed even stronger correlations and showed that NH_3 emissions in the barn are highly dependent on indoor housing temperature (Pereira et al., 2012; Adviento-Borbe et al., 2010; Wu et al., 2012). Recent meta-analyses also reported a positive relationship between NH_3 emissions and indoor temperature of cattle barns (Poteko et al., 2019; Qu et al., 2021; Sanchis et al., 2019). The correlation between temperature and emission rates showed variability amongst studies depending on the data, reported temperature ranges and housing factors included in the analysis. Poteko et al. (2019) investigated the relationship between NH_3 emissions and indoor temperature of cubicle housing in dairy systems where emissions showed a significant increase with rising temperatures. Bougouin et al. (2016) looking at the effect of the outside temperature on NH_3 emissions, also reported a positive correlation. Measurements of Zhang et al. (2005) proved that NH_3 emissions from the barn increased with increasing indoor temperature but also showed that the trend depended on floor type and manure management system. Sanchis et al. (2019) reported 1.47 g NH_3 cow^{-1} d^{-1} increase in NH_3 emissions when indoor temperature increased 1 °C. One reason for increasing NH_3 emissions with increasing temperature is the equilibrium between NH_3 in the

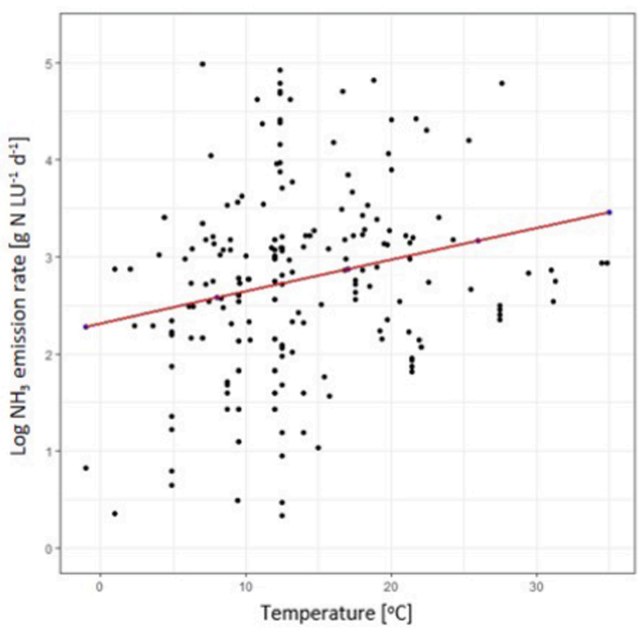

Fig. 5. Regression of log-transformed NH_3 emission rates over indoor barn temperature.

liquid phase and NH_3 in gas form. This equilibrium is highly dependent on Henry's constant which exponentially increases with temperature, therefore NH_3 emissions increase with increasing temperature (Sommer et al., 2006). Another reason is that higher urease activity results in higher NH_3 release from manure where urease activity increases exponentially with temperatures above 10 °C (Sommer et al., 2006; Monteny and Erisman, 1998).

Our dataset includes a wide range of emission measurements varying from 1.4 to 146 g NH_3 LU^{-1} d^{-1} where temperatures are reported, measurements conducted under different conditions and the data are spread over a wide range of temperature measurements (−1 to 34 °C). These differences can affect the linearity between NH_3 and temperature. Additionally, out of 293 NH_3 emission measurements recorded in the database, indoor temperature was only reported for 182 data points. It is important to highlight that the simultaneous reporting of temperature alongside with the emission data is highly relevant for a better evaluation of systems and data analysis.

Floor type nested within the different housing types was found as a highly significant factor influencing NH_3 emissions ($p < 0.001$, $n = 183$). There has not been a broad study looking into the effect of housing and floor type combinations on emissions so far because of the limited data availability. The wide availability data in DATAMAN allowed us to conduct such comparison between different systems. Comparing different housing and floor combinations showed that the lowest emissions were recorded from tied stalls with solid floors, whereas NH_3 emissions from feedlot with earthen floors showed the highest emissions. The comparison of same floor types for different housing systems showed the largest difference between tied stalls and cubicle housings·NH_3 emissions from tied stalls with solid floor were significantly lower than the emissions from cubicle housing with the same floor. A similar difference was also observed for slatted floors in tied stalls *vs* cubicle housing. Similar results were recorded in the study by Poteko et al. (2019), where a significant difference was observed between tied houses and cubicles, and tied houses showed much lower NH_3 emissions. Monteny and Erisman (1998), looking at the NH_3 emissions from dairy cattle barns, presented lower emissions from tied stalls (5–27 g cow^{-1} d^{-1}) than cubicle housing (20–45 g cow^{-1} d^{-1}). Lower emission releases from tied stalls can be explained by the smaller area of manure-covered floor and pit (Monteny, 2000). Nevertheless, the result is controversial in terms of animal welfare. This housing system was discouraged by some countries already decades ago (Royal Ministry of Agriculture, 2002). In fact, the literature on emissions from tied stalls is mainly concentrated in the 1990s and early 2000s. According to the RAMIRAN glossary, loose housing includes a deep litter bedding, and the abundant bedding material can also result in low NH_3 emissions. However, our study showed that NH_3 emissions from loose housing systems with solid floor were not significantly lower than those of cubicle housings with solid floor, and not significantly higher than those of tied stalls with solid floors.

The comparison of solid and slatted floors within identical housing systems, namely tied stalls and cubicle houses, showed no significant differences. Previous studies investigating the differences between floor types for identical housing systems reported similar results, since no difference was observed between solid and slatted floors for identical housing types (Poteko et al., 2019; Qu et al., 2021; Bougouin et al., 2016). Furthermore, Schiefler (2013) presented results over a year of measurements from barns with slatted and solid floor and found no difference between the two floor types.

3.3. N_2O emissions

The analysis showed that climate zone, animal category and housing and floor type combinations are key drivers for N_2O emissions ($n = 100$) (Table 4). Relative humidity and barn temperature were excluded from the models because no significant relationships with N_2O emissions were observed in any of the tested models. Most of the data recorded belong to the temperate wet zone ($n = 88$), while there is less data available for the temperate dry zone ($n = 12$). Despite the difference in data availability, the pairwise comparison showed that emissions from temperate wet zones were lower. Previous studies investigating N_2O emissions pointed out that the ratio of N_2O to N_2 depends on the moisture, acidity and nitrate concentration, where N_2O production increases under reduced moisture conditions (Dalal et al., 2003; Dong et al., 2006). The relationship between moisture content and N_2O emissions can explain the lower emissions from temperate wet zones in our study.

Not many studies compared N_2O emissions of beef and dairy cattle. For instance, Borhan et al. (2011) found N_2O emissions from beef feedlot at 0.68 g/d, while dairy cows in cubicle housings emitted 3.4 g/d. It is generally acknowledged that N_2O emission rates are related to N excretion, so that strategies to mitigate N_2O emission from cattle include reducing dietary N content or decreasing the protein/energy ratio (Dijkstra et al., 2013; Waldrip et al., 2016). It is also well known that dietary requirements of dairy and beef cattle, as well as those of lactating and non-lactating cows, are different. In Chile, Beltran et al. (2022) found the N intake of dairy cattle to range between 436 and 566 g N d^{-1}, while beef cattle ranged between 178 and 256 g N d^{-1}. Pereira et al. (2012) found that the higher CP content of the diet supplied to lactating cows led to significantly higher N_2O emissions relative to heifers and dry cows. Similar findings were reported by Zhu et al. (2014), with emission rates for milking cows averaging 37 g N_2O $animal^{-1}$ d^{-1}, whereas emission from heifers were 24 g N_2O $animal^{-1}$ d^{-1}. So, major diet differences can explain the emission rates of beef cattle being significantly lower than those of dairy cattle. Nonetheless, a clear imbalance in the number of observations in favor of dairy cattle (92 *vs* 8) must be recognized.

Several studies found N_2O emission rates to largely vary in relation to the manure management system in the barn, with great spatial and temporal variability and large differences caused by small differences in the barn setup (Sommer et al., 2013). N_2O is typically produced in interfaces where aerobic and anaerobic conditions meet; the spatial and temporal pattern of O_2 supply, as well as O_2 demand and reactive N compounds, is of particular importance for N_2O emissions (Petersen and Sommer, 2011). For instance, Baldini et al. (2016) found N_2O emissions to be significantly lower in cubicles with rubber mat compared to those with straw. The same authors found differences between solid floor systems related to the ease of cleaning such floors. In general, strictly anaerobic conditions (e.g., liquid systems) lead to lower emissions, whereas deep litter systems have higher emissions (Chadwick et al., 2011). Some studies negatively correlate NH_3 volatilization with the emission of N_2O (Adviento-Borbe et al., 2010). In our study, loose housings (i.e deep litter) with earthen floors turned out to be the combination of housing type and floor type with significantly higher N_2O emission rates, while feedlots with earthen floors showed the lowest N_2O emissions. Other combinations of floors and housings showed intermediate values not significantly different from each other. This is not only in partial agreement with the literature, but also with our results on NH_3 emissions, as feedlots with earthen floors showed the highest NH_3 emissions, while the NH_3 emission rates of loose housings with earthen floors were significantly lower.

Many studies highlight how predicting N_2O emissions from cattle housing is challenging (Webb et al., 2012; Redding et al., 2015; Waldrip et al., 2016). This study corroborates this evidence, concluding that housing type and floor system have an effect on N_2O emissions, although the available data in the literature (i.e., an average of 14 observations for each floor and housing combination considered) is not sufficient to draw detailed conclusions on all housing type and floor system combinations, especially when put in relation to other factors. DATAMAN does not currently contain information on manure removal frequency, floor characteristics (other than general floor typology), bedding type and amount, so the influence of manure management conditions on N_2O (but also NH_3 and CH_4) emissions could not be assessed in detail by our study. Further research should aim for the maximum detail when describing manure removal systems, aiming to understand the interactions with other factors (Chadwick et al., 2011; Sommer et al., 2013; Waldrip et al., 2016).

4. Conclusions

Despite the variability in the reported emissions, significant effects of key influencing factors on gaseous emissions were observed. CH_4 emissions were affected by environmental factors, with rates negatively correlated with temperature and relative humidity, while housing factors and climate zones did not have a significant effect on CH_4 emission rates. Nonetheless, CH_4 emissions are dominated by enteric fermentation. The analysis therefore does not suggest mitigation options related to manure and housing management, as the environmental factors seem to act mainly by influencing animal activity.

Regarding NH_3 emissions, apart from a well-known influence of environmental factors (relative humidity, temperature), comparing different housing type and floor type combinations showed that housing factors have an effect. However, not all housing systems can be suggested for future adoption, especially not those that show significantly lower emissions but are controversial from other points of view (i.e. tied stalls, for animal welfare reasons). The adoption of feedlots with earthen floors, and earthen floors in general, should be discouraged. In combination with loose housings, earthen floors showed the highest N_2O emission rates, but not the highest NH_3 emissions as in feedlots, probably because the conditions in feedlots do not favor nitrification/denitrification as much as volatilization. Slatted floors are not significantly different from solid floors, neither in terms of NH_3 emissions, as the literature has already shown, nor in terms of N_2O emissions.

The analysis also showed that the climate zone is a significant predictor of NH_3 and N_2O emission rates N_2O emission rates also differed between dairy and beef cattle. Overall, our study shows that it would be appropriate to consider improving housing systems to mitigate NH_3 and N_2O emissions, while CH_4 emission mitigation options are strongly related to environmental and animal conditions.

The DATAMAN database is the most extensive database on NH_3 and GHG emissions from manure management and ancillary data, but we observed substantial gaps in the original studies collated to the DATAMAN database. The DATAMAN database can be used to identify combinations of variables that are poorly studied to improve our overall understanding of emission rates for these gases. Our analysis highlights the needs of detailed reporting of ancillary variables along with emissions to be able to reduce uncertainties and improve comparative analysis in the future. Assessing emission rates under different combinations of housing and floor conditions in relation to other factors is crucial for establishing realistic emission factors for the different cattle management systems, which is essential to implement higher Tier methodologies for emission accounting in the national inventories. There is also the need to encourage research to investigate in more detail manure removal practices, manure residence time and specific floor characteristics, such as the draining capacity for direct transportation of urine to the manure storage, limiting the contact of urine with ureases from manure. More data are also needed for climatic zones that are typically less studied (e.g. temperate dry, tropical wet and dry).

In the future, a differentiation of cattle housing emission factors for climate zones and management systems is needed. Choosing appropriate mitigation options at the farm level is only possible when we have a better understanding of relationships between key drivers and gaseous emissions. Future research should focus on applying functional relationships between emission factors and key drivers to account for emission variations.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.09.007.

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