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# A meta-analysis of environmental factor effects on ammonia emissions from dairy cattle houses

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## Abstract

Livestock housing is one of the main sources of ammonia ($NH_3$) emissions from agriculture. Different management and environmental factors are known to affect $NH_3$ emissions from housing systems. The aim of this study was to quantitatively define the effect of temperature, wind speed, relative humidity, and ventilation rate in $NH_3$ release rates from dairy cattle housing by conducting a meta-analysis of published scientific results. A literature survey was performed to review studies published before January 2018 that have identified statistical relationships between $NH_3$ emissions and environmental factors such as air temperature, wind speed, relative humidity, or ventilation rate in dairy cattle housing. Experimental values were related using a mixed model analysis in order to analyze the effect of environmental factors on $NH_3$ emissions. For this exercise, a total of 19 peer-reviewed papers were considered and 27 different relations between air temperature and $NH_3$ emissions were used for the analysis. A significant effect of

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air temperature inside the barn and ventilation rate on $NH_3$ emissions was observed. Results showed that $NH_3$ emissions increased linearly with increasing air temperature (ºC) inside the barn by 1.47 g $NH_3$ $cow^{-1}$ $d^{-1}$ when temperature increased one degree. For ventilation rate, an increase of 100 $m^3$ $h^{-1}$ $cow^{-1}$ lead to increase $NH_3$ emissions by 0.007 g $NH_3$ $cow^{-1}$ $d^{-1}$. The equations obtained in this work might help to provide information on $NH_3$ barn-related emissions behavior under these environmental conditions, bearing in mind that other source of emissions such as diet composition and animal performance might be also affected by climate changes.

**Keywords**

$NH_3$; gaseous emissions; temperature; ventilation rate; dairy cows.

## 1. Introduction

Ammonia ($NH_3$) gaseous emissions from livestock buildings are a major environmental concern worldwide as their deposition contributes to the eutrophication of terrestrial and aquatic ecosystems, as well as the acidification of soils, thus reducing plant biodiversity and contribute to the formation of secondary particulate matter, which is associated to respiratory and cardiovascular diseases (Behera et al., 2013; IPCC, 2014). About 94% of global anthropogenic emissions of $NH_3$ to the atmosphere are originated from the agricultural sector and about 64% are associated with livestock production (Steinfeld et al., 2006), being dairy farming a major source (Hristov et al., 2011; Külling et al., 2001).

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In livestock buildings, $NH_3$ is released as a result of microbiological hydrolysis of urea and uric acid by urease to form $NH_4^+$ and its subsequent volatilization to $NH_3$ (Bouwman et al., 1997). The total amount of $NH_3$ being emitted to the atmosphere mainly depends on manure excretion and its characteristics (e.g. total ammonia nitrogen, TAN). The percentage of this TAN emitted as $NH_3$ depends on multiple factors such as manure management systems, livestock management practices and animal behavior (Bjerg et al., 2013). Environmental conditions play also a crucial role on the rate of the excreted nitrogen that will be released as $NH_3$. Factors such as manure temperature (Ferm et al., 2005; Hristov et al., 2011; Jungbluth, Hartung, & Brose, 2001; Montes et al., 2009), air temperature, relative humidity, wind speed and ventilation rates (Hempel et al., 2016; Monteny, Schulte, Elzing, & Lamaker, 1998; Ngwabie, Vanderzaag, Jayasudara, & Wagner-Riddle, 2014; Rong, Liu, Pedersen, & Zhang, 2014; Saha et al., 2014) have demonstrated to strongly affect $NH_3$ emissions.

When modelling mass and energy balances at farm or system scale, gaseous emissions should be included as a major nutrient leak. The simplification inherent to models when assessing emissions limit their ability to refine results since they normally use equations that allow generalizing the effect of major parameter on emissions. An approximation for environmental parameter effects on gaseous release rates can be found already implemented in some specific models such as Manure-DNDC (Li et al., 2012), which assesses the degradation of manure in livestock systems. However, in those whole farm system models such as $\text{SIMS}_{\text{DAIRY}}$ (Del Prado et al., 2011), which simulate housing emissions using empirical modelling approaches (Webb & Misselbrook, 2004) and have TAN excretion as the main emission drivers, these environmental effects have not yet been considered.

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This study was undertaken to collate and analyze published data on $NH_3$ emissions from dairy cattle housing with the aim of quantifying the effect of environmental factors in $NH_3$ emissions from dairy cattle housing and potentially be useful for refinement of modelling approaches like $SIMS_{DAIRY}$. The aim of this study was to quantitatively define the effect of temperature, wind speed, relative humidity, and ventilation rate in $NH_3$ release rates from dairy cattle housing by conducting a meta-analysis of published scientific results. This study is limited to environmental conditions affecting $NH_3$ release rates, other major emission drivers such as TAN excretion or management are not considered in this work.

## 2. Materials and methods

A literature survey was performed to review studies published up to the year 2017 inclusively that have identified statistical relationships between $NH_3$ emissions and environmental factors such as air temperature, wind speed, relative humidity, or ventilation rate in dairy cattle housing.

The literature review was carried out searching information in the Web of Knowledge, Science Direct, CAB direct (CAB International), and Scopus databases entering the following keywords: ammonia or $NH_3$ emission, temperature, ventilation rate, wind speed, relative humidity, dairy cattle, animal housing.

Articles were selected according to the following criteria: (1) publications were in peer-reviewed journals; (2) dairy cattle were used as experimental animals; (3) it was reported the effect of air temperature, ventilation rate, indoor wind speed, or relative humidity on $NH_3$ emissions inside the barn; and (4) quantitative information of the effect of these environmental

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factors on $NH_3$ emissions was reported. If these results were presented only in graphs without reporting the corresponding numeric values, we quantified the values using the software Engauge Digitizer version 9.5. This software allows extracting numeric values from images or graphs. Measurement methods of emissions, housing system, flooring type and manure management systems, were identified but were not included in the analysis as an independent factor.

Data obtained from the articles were normalized to the same units: temperature in ºC, ventilation rate in $m^3$ $h^{-1}$ $cow^{-1}$, wind speed in m $s^{-1}$, relative humidity in %, and $NH_3$ emissions in g $NH_3$ $cow^{-1}$ $d^{-1}$. To analyze the effect of environmental factors on $NH_3$ emissions, the values were related using a mixed model analysis (SAS, 2009) following the procedure described by St-Pierre (2001). Linear, quadratic and third degree polynomial fitting equations were tested. As described in the following section, linear equations presented the best fitting and lowest residuals. The mixed model analysis is useful when data are obtained from multiple studies. Therefore, it was necessary to analyze not only fixed effects of the dependent variables, but also the study and its interactions as random effects. This methodology allows isolating the relative effect of the studied variable (e.g. temperature) on $NH_3$ emissions regardless absolute emission values. Therefore, factors such as animal performance, TAN excretion, etc. which strongly influence emissions can be neglected.

## 3. Results and discussion

### 3.1. Description of the dataset

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A total of 19 articles were selected for this meta-analysis (Table 1). Regarding the effect of air temperature inside the barn, a total of 14 peer-reviewed published research articles were selected. Reviewed articles reported studies from 1998 to 2014, conducted in nine countries (Sweden, Netherlands, USA, Denmark, UK, Poland, Germany, Canada and Lithuania).

Table 1 compiles reported $NH_3$ emission rates related to environmental factors obtained from the studies included in the meta-analysis, as well as the number of animals in the barn, the ventilation system, flooring type, manure handling, and the method used to measure $NH_3$ emissions. When the barn was a closed-barn, ventilation type was identified either as natural or mechanical ventilation. However, in some cases (Bjorneberg et al., 2009; Leytem, Dungan, Bjorneberg, & Koehn, 2011) the farm studied was an open-lot system dairy farm, without controlled ventilation system. Powell et al., (2008a,b) and Bagdonienė and Bleizgys (2014) carried out their studies in chambers. The flooring systems were identified as solid or slatted floor and the manure management system as scrapped or flushed.

Information regarding measuring methods for $NH_3$ emissions is also included in Table 1. $NH_3$ concentration was mainly measured by photoacoustic methods (Adviento-Borbe et al., 2010; Leytem et al., 2011; Leytem, Dungan, Bjorneberg, & Koehn, 2012; Ngwabie, Jeppsson, Gustaffson, & Nimmermark, 2011; Ngwabie, Jeppsson, Nimmermark, Swensson, & Gustafsson, 2009; Ngwabie et al., 2014; Snell, Seipelt, & Van Den Weghe, 2003; Zhang et al., 2005) or by spectroscopy (Bagdonienė and Bleizgys, 2014; Bjorneberg et al., 2009; Gustafsson et al., 2005; Powell et al., 2008a,b). Angrecka and Herbut (2014) and Kavolelis (2006) measured $NH_3$ concentrations using Dräger detectors whereas Flesch et al. (2009) and

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Misselbrook et al. (1998) measured concentrations using laser or absorption flasks, respectively. $NH_3$ emissions were determined in most of the studies by mass balances considering $NH_3$ concentrations and ventilation rates (Adviento-Borbe et al., 2010; Angrecka and Herbut , 2014; Bagdonienė and Bleizgys, 2014; Kavolelis, 2006; Misselbrook et al., 1998; Ngwabie et al., 2014, 2011, 2009; Powell et al., 2008a,b; Snell et al., 2003; Zhang et al., 2005). Other authors (Bjorneberg et al., 2009; Dore et al., 2004; Flesch et al., 2009; Leytem et al., 2011, 2012) used the Lagrange inverse dispersion technique to quantify $NH_3$ emissions. Only one study quantified emissions using a static chamber (Adviento-Borbe et al., 2010). The number of animals in each experiment varied from 16 to 10,000.

From these articles, 27 different relations between air temperature and $NH_3$ emissions were considered for the analysis (see SUPP. Material SP1). The effect of ventilation rate on $NH_3$ emissions was studied through 11 different relations obtained from 6 published studies (SUPP. Material SP2). The effect of wind speed and relative humidity was studied through the results of 5 and 6 published studies, respectively. When the same publication contained more than one datasets or experimental results on the same topic (e.g. Zhang et al., 2005 presents 10 datasets relating temperature and emissions), these were considered separately as independent studies.

Table 2 shows the descriptive statistics of the environmental factors and $NH_3$ emissions included in the database. $NH_3$ emission rates ranged from 0.3 to 245.7 g $NH_3$ cow$^{-1}$ d$^{-1}$. A wide range was observed for temperature, relative humidity, ventilation rate and air speed at animal level. This suggests that results from a wide range of climatic conditions and barn designs were

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analyzed. The statistical analysis showed a significant effect of temperature, which is described in the following section.

In our study, no wind speed neither relative humidity presented statistically significant effects on $NH_3$ emissions. According to Snoek et al. (2014), the rate of $NH_3$ volatilization depends on the mass transfer coefficient, which depends on wind speed at manure level, thus leading to a positive correlation between both parameters.  Nevertheless, data from wind speed measurements used in this analysis were not performed at manure level but at barn level. It is known that, at barn scale, air velocities might present a high variability. This might be also happening with humidity data and should explain the lack of significant effects on $NH_3$ emissions observed by Bougouin et al. (2016) and Simsek et al. (2012).

### 3.2. Effect of temperature on $NH_3$ emissions

Figure 1 shows the relationship between temperature and $NH_3$ emissions for the whole dataset (see Table SP1). On average, $NH_3$ emissions increased linearly with increasing air temperature inside the barn (ºC). According to Meisinger and Jokela (2000), higher temperatures promote $NH_3$ losses by decreasing the solubility of $NH_3$ gas in the soil solution and by increasing the proportion of TAN as $NH_3$ gas. Urease activity is also affected by temperature, being reduced at temperatures lower than 10 ºC and increased between 10 and 40 ºC (Sommer et al., 2006). The amount of volatile $NH_3$ release to the atmosphere depends as well on the equilibrium between $NH_3$ in the liquid and in the gas phase. This equilibrium is strictly temperature dependent (Monteny & Erisman, 1998).

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Several of the selected studies for the meta-analysis have shown a significant positive correlation between temperature in the barn and $NH_3$ emissions (Adviento-Borbe et al., 2010; Doorn, Natschke, & Meeuwissen, 2002; Gustafsson et al., 2005; Kavolelis, 2006; Misselbrook et al., 1998; Ngwabie et al., 2011; Zhang et al., 2005). These authors found that $NH_3$ emissions increased with increasing air temperature, but in some cases, this increase was highly dependent on floor type and manure system (Zhang et al., 2005). These external effects might be also causing the presence of non-linear relationships at some of the datasets.

The rest of the articles selected did not quantified the relationship between air temperature and $NH_3$ emissions, however they found diurnal and seasonal patterns of $NH_3$ emissions associated with air temperature (Bjorneberg et al., 2009; Dore et al., 2004; Flesch et al., 2009; Leytem et al., 2012, 2011; Ngwabie et al., 2009; Powell et al., 2008a,b).

Table 3 shows the statistical parameters obtained through the meta-analysis. According to our results, when temperature increases one degree, $NH_3$ emissions increase by 1.47 g $cow^{-1}$ $d^{-1}$. Liu et al. (2017) found linear regression equations between $NH_3$ emissions, air temperature and crude protein content of feed in open-lot, free-stall and tie-stall dairy barns. These authors found a stronger effect of temperature on emissions, thus each 1ºC increase in air temperature, $NH_3$ emissions increased between 2.7 and 2.4 g $cow^{-1}$ $d^{-1}$. It must be considered that the equation obtained in this work has been developed considering only those studies which studied the effect of temperature on $NH_3$ emissions, by obtaining emission factors at the same location and conditions except for temperature. However, Liu et al. (2017) included also studies showing a

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unique value of temperature and $NH_3$ emissions, which might lead to bias when multiple factors affect emissions at a single point (e.g. higher milk yields for lower temperatures).

Emission factors obtained using the equation developed in this work are within the range used for inventories. As an example, the European Environmental Agency guidelines for national emission inventories (EEA, 2016) suggest a Tier 1 emission factor between 16.9 and 19.2 kg $NH_3$ $AAP^{-1}$ $year^{-1}$ (AAP: Average Annual Population). Using values provided in Table 3, and an average temperature of 15ºC, it results in an emission factor of 17.53 kg $NH_3$ $cow^{-1}$ $year^{-1}$.

The effect of temperature on $NH_3$ emissions as a percentage of TAN can be also expressed following to Equation 1 (within the temperature range from −8 to 35 ºC).

$$NH_3 \text{ emissions (g [N-}NH_3\text{] g}^{-1}\text{ [TAN excreted])} = 0.007\ \textit{Temperature}\ (^{\circ}\text{C}) + 0.12 \qquad \text{(Equation 1)}$$

This Equation was obtained from Table 2 by transforming units and considering a nitrogen excretion rate of 105 kg N $year^{-1}$ $cow^{-1}$ and a proportion of TAN 60% over N excreted (EEA, 2016).

### 3.3. Effect of ventilation rate on $NH_3$ emissions

According to Blanes-Vidal (2008), higher ventilation rates cause in general, higher air velocities inside the barn, and therefore higher gaseous emissions. Several authors have studied the relationship between ventilation rate and $NH_3$ emissions with a general positive correlation between both terms (Kavolelis, 2003; Philippe, Cabaraux, & Nicks, 2011; Samer et al., 2012). Figure 2 depicts the relationship found in this work for ammonia $NH_3$ and ventilation rates. A positive linear relationship was also observed in this case. As also explained before regarding

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temperature effect, despite some datasets present non-linear relationship between ventilation rate and $NH_3$ emissions, other factors (such as management, environmental constraints, etc.) might condition individual results.

According to the statistical analysis (Table 4), an increase of 100 $m^3\ h^{-1}\ cow^{-1}$ lead to increase $NH_3$ emissions by 0.007 g $NH_3\ cow^{-1}\ d^{-1}$. The following equation (Equation 2) shows the $NH_3$ emissions expressed as a percentage of TAN. For this purpose, values of nitrogen excretion and proportion of TAN in the dairy cattle manure excreted have been obtained from the EEA (2016) Guidelines. Ventilation rate values in Equation 2 ranged from 40 to 1,814 $m^3\ hour^{-1}\ cow^{-1}$.

$$NH_3 \text{ emissions } (g\ [N\text{-}NH_3]\ g^{-1}\ [TAN\ excreted]) = 0.00016\ \textit{Ventilation Rate}\ (m^3\ h^{-1}\ cow^{-1}) + 0.11$$

(Equation 2)

It must be considered that there is an interaction between temperature and ventilation rate. It is known that the difference of temperatures inside and outside of the barn affects ventilation rates (Sommer et al., 2013). Bearing this fact in mind, it must be considered that neither the wind speed nor the ventilation rates are necessarily the dominant factor of influence for the $NH_3$ concentration in the air of naturally ventilated dairy houses. Therefore, only one of the two equations presented in this work should be used at once to avoid overestimating the effect of these effects on emissions.

An increase in gaseous emissions due to global warming might be expected in the future (IPCC, 2014), creating great challenges for animal production and the sustainability of livestock systems, particularly in countries with warmer climates such as the Mediterranean (Pereira, Misselbrook, Chadwick, Coutinho, & Trindade, 2012). The equations obtained in this work

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might help to provide information on $NH_3$ barn-related emissions behavior under these environmental conditions, bearing in mind that other major emission drivers such as diet composition and animal performance might be also affected by climate changes.

## 4. Conclusion

This study was designed to quantify the effect of environmental factors in $NH_3$ emissions from dairy cattle housing. The statistical analysis showed a significant effect of air temperature inside the barn and ventilation rate on $NH_3$ emissions. The following conclusions can be drawn from this study:

Air temperature inside the barn is the most important environmental factor affecting $NH_3$ emissions. $NH_3$ emissions increased linearly with increasing air temperature (ºC) inside the barn by 1.47 g $NH_3$ cow$^{-1}$ d$^{-1}$ when temperature increased one degree.

Ventilation rate also produce a linear increase in $NH_3$ emissions. An increase of 100 m$^3$ h$^{-1}$ cow$^{-1}$ lead to increment $NH_3$ emissions by 0.007 g $NH_3$ cow$^{-1}$ d$^{-1}$. However, due to the close correlation between both factors, a confounded effect of ventilation rate with temperature may exist.

No effects between $NH_3$ emissions and wind speed or relative humidity were found significant through the statistical analysis probably due to the high variability of both parameters within the barn environment.

Our equations to predict $NH_3$ emissions would be very helpful to provide information on $NH_3$ barn-related emissions behavior under these environmental conditions, bearing in mind that

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other major emission drivers such as diet composition and animal performance might be also affected by climate changes.

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