

Occupational exposure to carbon dioxide, ammonia and hydrogen sulphide on livestock farms in north-west Spain

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Abstract

The influence of the type of farming on harmful gas exposures to carbon dioxide (CO₂), ammonia (NH₃) and hydrogen sulphide (H₂S) was assessed from the perspective of animal welfare and occupational hygiene. Summer data of H₂S, NH₃ and CO₂ concentrations and of environmental parameters were collected from 31 farms. The indices of exposure for long-term exposures to NH₃ suggest the lowest acceptability of exposure was observed on poultry farms. CO₂ had the highest dependence on production activity. For H₂S, no differences were found based on farming activity. Both the stocking density and volume of air available affected the daily exposure and the index of exposure to CO₂. Significant differences were observed between hourly CO₂ concentrations, depending on the level of activity inside the building. A positive correlation was found between gas concentrations and temperature increase. All values of daily and short-term exposures were below exposure limit values, which suggests that exposure conditions were appropriate for workers' health during the measurement period. Analysis of the working hours and average hourly concentration of gases during the times of day, with presence of workers inside the farm buildings, revealed significant differences for CO₂.

Key-words

livestock farms, harmful gases, animal welfare, occupational hygiene

Abbreviations

c_i – i -th concentration; DE – Daily Exposure; EVL – Exposure Limit Values; IE – Index of Exposure; t – time of exposure; t_i – measurement interval

INTRODUCTION

Gas emissions from livestock farms affect environmental pollution, animal production and welfare, and workers' health. A number of authors have analysed air emissions from farms and their positive or negative influence on many aspects related to animals, humans and the environment [1, 2, 3, 4, 5, 6, 7, 8, 9].

In the EU, the emission of gases such as sulphur dioxide (SO₂), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and ammonia (NH₃) into the atmosphere is regulated under European Directive 2001/81/EC on National Emission Ceilings [10]. This directive allows member states to implement the measures required to comply with national emission ceilings. The control and reduction of emissions is a key factor in every activity, including animal production.

High concentrations of gases can seriously affect animal health and production. At high concentrations, NH₃ can cause ulceration of the eyes and irritation to the respiratory tract of pigs [11, 12], thus reducing lung bacterial clearance [13, 14]. In addition, high NH₃ concentrations reduce feed consumption and cause daily weight gain [15]. At high concentrations, H₂S causes respiratory problems [11], and other gases such as carbon dioxide, CO₂, or methane, CH₄, displace oxygen, which can cause suffocation or asphyxiation [12].

The levels of gas emissions from farms are dependent on many factors, including: method of manure handling, ventilation mode, growth stage of animals [7, 16], floor type [17], animal feeding and activity level [18], seasonal variations [19] and level of cleaning [20]. Kim *et al.* [7, 21] found that NH₃ and H₂S concentrations and emissions were higher on pig farms managed with deep-pit manure systems with slats and mechanical ventilation than in other types of swine housing. In agreement with these observations, Zhang *et al.* [17] found the lowest ammonia emission from naturally-ventilated dairy cattle buildings, in buildings with solid floors with a smooth surface, scraper and drain. Conversely, in organic housing systems for fattening pigs, the farms with daily scraper cleaning or slatted floor systems showed significantly lower NH₃ emissions than the farms with bi-weekly manual removal of manure [6].

Feeding operations, particularly with feed concentrates, can cause the emission of toxic gases, vapour and particles [5]. Feed composition may affect the composition of the air on the farm. Robertson *et al.* [18] found correspondences between NH₃ emissions and the actual total protein consumed on broiler farms.

Inside air temperature may affect gas emissions. Jeppsson [22] observed that the increase in NH₃ emissions with air temperature followed an exponential pattern, and found correlations between CO₂ emissions and temperature in an uninsulated experimental building with pigs. In addition to diurnal variations, seasonal variations can be observed. On broiler farms, Liang *et al.* [19] observed that

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NH₃ emission rates from houses were higher in summer than in winter, although NH₃ concentration might be much lower in summer.

With regard to occupational hygiene, pollutants such as H₂S, NH₃, volatile organic compounds, particulate matter, or endotoxins may affect workers' health [23]. A number of analyses of indoor air quality on pig farms showed that workers' health and exposure to air pollutants are correlated [14, 24]. Long and continuous exposures to air pollutants may result in respiratory diseases, some of them chronic [7,25]. The hazard of pollutants increases with the time spent by workers inside farm buildings at unacceptable exposure values.

In Spain, occupational exposure limit values are regulated under the document 'Occupational exposure limits for chemicals in Spain' [26], based on Royal Decree 374/2001 on safety and health protection against risks from chemical agents in the workplace [27].

The research presented in this paper was carried out in Galicia, NW Spain. With an area of 29,365 km², Galicia is a key region for the Spanish agricultural livestock production industry. According to the Galician Yearbook of Agricultural Statistics [28], the number of cattle farms in Galicia amounts to 47,163, with 343,298 dairy cows and 218,925 beef cows. With regard to pig farms, a total of 59,235 family farms with up to 107, 507 pigs and 1,066 factory farms with up to 349,547 pigs are registered. In recent decades, livestock farming has undergone substantial changes, and farm facilities and management systems have been adapted. The increase in farm size and the availability of labour are two of the factors behind the evolution of the industry aimed at improving production efficiency.

Gas emissions from livestock farms can be affected by factors such as, among others, livestock species, management system, farm facilities, animal welfare, animal production or occupational health and hygiene. The objective of this paper was to determine the influence of farm characteristics on H₂S, NH₃ and CO₂ concentrations from the perspective of occupational health and hygiene, and to assess the risks of exposure for workers.

MATERIALS AND METHODS

The concentrations of H₂S, NH₃ and CO₂ and two environmental parameters, relative humidity and temperature, were measured and recorded on 31 cattle, pig and poultry farms of Galicia, NW Spain, during the summer. The characteristics of the cattle, pig and poultry farms studied are presented in Tables 1, 2 and 3, respectively. Cattle farms followed two management systems: intensive farming (cows kept indoors) or semi-extensive grazing, and three possible types of housing: tie stall housing, collective housing or freestall housing with solid (scraper or water-flow cleaning) or slatted floors. Pig farms used intensive farming. Pig housing facilities had slatted floors and were equipped with automatic concentrate-dispensing systems. Fattening pigs were housed in collective facilities, but individual stalls were used for pregnant sows, breeding sows and piglets. Finally, poultry fattening farms followed an intensive indoor or outdoor model, with cleaning performed at the end of each rearing cycle. Poultry housing was collective and the buildings were equipped with a full-bed system and automatic feeders.

Table 1. Characteristics of cattle farms studied

Farm identification	Management system	Type of housing system	Cleaning system	Built-up area (m ²)	Total air volume, (m ³)	Stocking density, (kg/m ²)	Volume of air available per unit live weight (m ³ /kg)
BC ^a _01	Semi-extensive	Tie-stall	Slats	316.25	1,344.06	75.89	0.06
BC ^a _02	Semi-extensive	Freestall	Slats	330.00	1,650.00	90.91	0.06
BC ^a _03	Intensive	Collective box	Slats	265.00	927.50	48.57	0.07
BC ^a _04	Intensive	Collective box	Slats	197.40	838.95	50.15	0.08
BC ^a _05	Semi-extensive	Tie-stall/Box	Slats	317.00	1,190.00	71.40	0.05
BC ^a _06	Intensive	Freestall/Box	Slats	658.00	2,368.80	60.00	0.06
DC ^b _01	Intensive	Freestall	Slats	896.00	5381.60	27.90	0.22
DC ^b _02	Intensive	Freestall	Scraper	816.00	4,284.00	37.38	0.14
DC ^b _03	Intensive	Freestall	Water flow	7,080.00	44,250.00	25.42	0.25
DC ^b _04	Intensive	Freestall	Scraper	1,485.00	8,500.00	34.00	0.17
DC ^b _05	Intensive	Freestall	Slats	735.00	3,659.69	28.06	0.18
DC ^b _06	Intensive	Freestall	Scraper	1,651.20	9,081.60	32.20	0.17

^aBC – Beef Cattle; ^bDC – Dairy Cattle

Table 2. Characteristics of pig farms studied

Farm identification	Type of housing system	Ventilation system	Built-up area (m ²)	Total air volume (m ³)	Stocking density (kg/m ²)	Volume of air available per unit live weight (m ³ /kg)
FP ^a _01	Collective box	Exhaust fans	455.40	1,639.44	65.88	0.05
PS ^b _02	Freestall	Exhaust fans	77.00	288.75	30.91	0.12
BS ^c _03	Crates	Exhaust fans	297.00	1,113.75	20.20	0.19
FP ^a _04	Collective box	Exhaust fans	560.00	2,352.00	69.64	0.06
PS ^b _05	Freestall	Natural	241.50	966.00	17.39	0.23
BS ^c _06	Crates	Natural	252.00	1,058.40	11.90	0.35
FP ^a _07	Collective box	Exhaust fans	451.25	1,489.13	70.60	0.05
PS ^b _08	Crates	Exhaust fans	839.50	3,190.10	23.93	0.16
BS ^c _09	Crates	Natural	336.00	772.80	25.00	0.09
PS ^b _10	Box/Crates	Natural	176.40	564.48	29.76	0.11
BS ^c _11	Crates	Exhaust fans	582.40	1,659.84	17.00	0.17
FP ^a _12	Collective box	Exhaust fans	743.40	2,155.86	64.57	0.04

^aFP – fattening pigs; ^bPS – pregnant sows; ^cBS – breeding sows and piglets

Table 3. Characteristics of poultry farms studied

Farm identification	Ventilation system	Built-up area (m ²)	Total air volume (m ³)	Stocking density (kg/m ²)	Volume of air available per unit live weight (m ³ /kg)
FB ^a _01	Exhaust fans	1,996.80	7,488.00	29.70	4160.00
FB ^a _02	Exhaust fans	793.80	2,698.92	12.60	6,747.30
FB ^a _03	Exhaust fans	1,972.00	8,085.20	14.00	10,106.50
FT ^b _04	Transverse ventilation	1,960.00	8,134.00	26.12	2,033.50
FT ^b _05	Natural	1,440.00	5,184.00	13.89	2,592.00
FB ^a _06	Exhaust fans	1,382.40	7,188.48	1.06	102,692.57
FB ^a _07	Exhaust fans	950.00	4,085.00	7.83	5,106.25

^aFB – fattening broilers; ^bFT – fattening turkeys

Two instruments were used to measure gas concentrations and environmental parameters: a data-logger, designed to measure temperature, relative humidity and illuminance (KH100, Kimo Instruments S.L., Badalona, Spain), and a multi-gas detector (MX2100, ISC-OLDHAM, Oakdale, USA). The measurement equipment was placed in a representative area inside each building, avoiding direct solar radiation and proximity to ventilation openings, and installed at 0.8 m working height. In each building, temperature, relative humidity and illuminance data were recorded from 09:00 at 10-min intervals for 24 h. The measurement accuracy was $\pm 0.4^{\circ}\text{C}$ ($+5^{\circ}\text{C} \leq T < +70^{\circ}\text{C}$) for temperature, 2.95% for relative humidity (between 18°C - 28°C) and $\pm 10\%$ for illuminance. H₂S, NH₃ and CO₂ concentrations were recorded from 9:00-21:00 h at 1-min intervals, so that the measurement period coincided with the working day. Accuracy of gas measurement was $\pm 5\%$.

To assess workers' risk from exposure to harmful gases, the 'Technical guide for the assessment and prevention of occupational risks associated to the exposure to chemical agents' [29] was used. This guide implements the Spanish legislation in force, Royal Decree 374/2001 on safety and health protection against risks from chemical agents in the workplace [30]. The technical guide defines Daily Exposure (DE), Short-term Exposure (SE) and Exposure Limit Values (ELV). To assess occupational risks, gas concentrations must be measured in the breathing zone of the workers. Because farm workers must adopt different positions, measurements were made at a 0.8 m working height.

Exposure (E) was defined as the time-weighted average of the concentration of a chemical agent in the breathing zone of a worker, measured or calculated from Eqn (1).

$$E = \frac{\sum c_i t_i}{t} \text{ Eqn (1)}$$

where c_i is the i -th concentration, t_i is the measurement interval, and t is the time of exposure.

DE was determined considering the time of exposure as equivalent to an actual working day of 8 hours. SE was defined as the average of the concentration of a chemical agent in the breathing zone of a worker, measured or calculated for any 15-min interval throughout the working day. For CO₂, SE measurements included exposure for periods of 30 min (SE-30').

To prevent most workers from suffering the adverse effects associated with exposure to chemical agents in the workplace, the Spanish legislation has established reference values, termed exposure limit values (ELV), both for DE (ELV-DE) and for SE (ELV-SE), and included in the document

'Occupational exposure limits for chemicals in Spain 2008' [26]. Table 4 summarises the limit values for the gases analysed in this paper.

Table 4. Daily and short-term occupational exposure limit values for chemical agents in Spain

Chemical agent	ELV-DE ^a	ELV-SE ^b
H ₂ S (ppm)	10.00	15.00
NH ₃ (ppm)	20.00	50.00
CO ₂ (%)	0.50	-

^aELV-DE – daily exposure limit value

^bELV-SE – short-term exposure limit value

To assess daily exposure, the Index of Exposure (IE) was calculated from a small number of samples (equal to or below 6) according to UNE-EN 689 standard [30], which was taken as a reference for the 'NTP 583: Occupational exposure assessment to chemical agents' [29]. The expression in Eqn (2) was used to determine the value of IE. In Eqn (2), DE is daily exposure and ELV-DE is the daily exposure limit value established in the legislation (Tab. 4):

$$IE = \frac{DE}{ELV - DE} \text{ Eqn (2)}$$

If $IE \leq 0.1$, exposure was acceptable and it could be considered unlikely that daily exposure exceeded the limit value during any working day. Exposure was not acceptable if $IE > 1$. To assess SE, the value of exposure was compared with ELV-SE. The short-term exposure limit value could not be exceeded during the working day. For substances that were assigned an ELV-DE, but not an ELV-SE (in this case, CO₂), the Limits of Deviation (LD) were applied. The limits of deviation specify that exposures must not exceed a value of $3 \times ELV-DE$ for more than a total of 30 min during the whole working day, and must never exceed a value of $5 \times ELV-DE$. Accordingly, the value of SE-30' for CO₂ must be lower than 1.50% and CO₂ concentration must never exceed 2.50%.

The ideal concentrations of harmful gases for animals housed in farm buildings are above the values defined for workers. Consequently, by verifying that the values of gas concentrations are admissible for workers, we ensure that harmful gas concentrations are admissible for animals.

After the data of environmental parameters were obtained for every farm, the values of the variables of analysis DE, SE, SE-30' and IE were determined. These values were analysed using the SPSS statistical package (Copyright © SPSS Inc., an IBM Company, Chicago, IL). An ANOVA was performed to determine significant differences between the values of the variables depending on farm characteristics (animal species, type of farming, live weight by unit area, and volume of air available per unit live weight). The analysis considered the length of the working day and the moment when the operations were performed on each farm. A *post-hoc* HSD-Tukey's test was performed to determine the groups that showed significant differences. In addition, the correlations between environmental conditions (temperature and relative humidity) and gas concentrations were determined.

RESULTS AND DISCUSSION

After the values of environmental parameters were obtained, the values of daily exposure to H₂S, NH₃ and

CO₂, short-term exposure to NH₃ and H₂S, and maximum exposure and SE-30' to CO₂ were determined. Table 5 shows the results obtained for the farms considered.

Table 5. Exposures calculated for each farm

Farm identification	DE ^a			SE ^b		Emax ^c		SE-30' ^d
	NH ₃ (ppm)	H ₂ S (ppm)	CO ₂ (%)	NH ₃ (ppm)	H ₂ S (ppm)	CO ₂ (%)	CO ₂ (%)	
BC ^f _01	3.41	0.00	0.10	5.53	0.00	0.13	0.20	
BC ^f _02	0.00	0.00	0.04	0.00	0.00	0.10	0.20	
BC ^f _03	0.15	0.00	0.15	1.00	0.00	0.10	0.10	
BC ^f _04	1.15	0.00	0.14	3.47	0.00	0.10	0.20	
BC ^f _05	0.61	0.00	0.12	1.00	0.00	0.10	0.10	
BC ^f _06	0.00	0.00	0.08	0.00	0.00	0.10	0.10	
DC ^g _01	0.07	0.02	0.15	1.00	0.73	0.10	0.10	
DC ^g _02	0.00	0.00	0.15	0.00	0.00	0.10	0.10	
DC ^g _03	0.00	0.00	0.15	0.00	0.00	0.10	0.10	
DC ^g _04	0.21	0.00	0.15	1.00	0.00	0.10	0.10	
DC ^g _05	0.00	0.00	0.15	0.00	0.13	0.10	0.10	
DC ^g _06	0.52	0.00	0.15	1.00	0.00	0.10	0.10	
FP ^h _01	2.59	0.29	0.15	2.93	1.00	0.10	0.20	
PS ⁱ _02	0.26	0.00	0.15	1.00	0.00	0.10	0.10	
BS ^j _03	4.11	0.00	0.16	4.60	0.00	0.19	0.20	
FP ^h _04	6.30	0.00	0.15	5.00	0.00	0.10	0.10	
PS ⁱ _05	2.08	0.00	0.15	2.47	0.00	0.11	0.20	
BS ^j _06	4.69	0.00	0.16	5.60	0.00	0.17	0.20	
FP ^h _07	1.11	0.00	0.15	2.33	0.00	0.11	0.30	
PS ⁱ _08	0.66	0.00	0.09	1.20	0.00	0.10	0.10	
BS ^j _09	3.72	0.00	0.15	4.00	0.00	0.10	0.10	
PS ⁱ _10	0.71	0.01	0.15	1.00	0.20	0.10	0.10	
BS ^j _11	1.38	0.00	0.15	1.80	0.00	0.10	0.10	
FP ^h _12	17.59	0.00	0.30	16.00	0.00	0.20	0.20	
FB ^k _01	22.54	0.10	0.21	20.93	0.67	0.20	0.20	
FB ^k _02	7.53	0.00	0.38	8.07	0.00	0.40	0.40	
FB ^k _03	11.38	0.00	0.29	17.27	0.00	0.39	0.40	
FT ^l _04	10.41	0.00	0.19	15.93	0.00	0.21	0.30	
FT ^l _05	6.23	0.00	0.19	7.00	0.00	0.25	0.30	
FB ^k _06	2.71	0.00	0.44	3.00	0.00	0.30	0.30	
FB ^k _07	4.84	0.00	0.19	8.67	0.00	0.21	0.30	
ELV ^e	20.00	10.00	0.50	50.00	15.00	2.50	1.50	

^a DE – daily exposure; ^b SE – short-term exposure; ^c Emax – Maximum exposure during the whole measurement period; ^d SE-30' – exposure for any 30-min interval; ^e ELV – exposure limit value; ^f BC – beef cattle; ^g DC – dairy cattle; ^h FP – fattening pigs; ⁱ PS – pregnant sows; ^j BS – breeding sows and piglets; ^k FB – fattening broilers; ^l FT – fattening turkeys

Exposures to NH₃, both DE and SE, were null on 16% of the farms, all of which are cattle farms. Poultry farms showed the highest values of exposure to NH₃, followed by pig farms and beef cattle farms, which is consistent with the results reported by Wathes *et al.* [31] and Koerkamp *et al.* [32]. One of the broiler farms exceeded the short-term exposure limit value, and one of the pig-fattening farms came near to that value.

The hourly evolution of NH₃ concentrations on pig farms revealed an increase in concentrations during the morning and a tendency to stability for the rest of the measurement period. Such a pattern had already been observed by Jeppsson [22], who detected a slightly higher NH₃ emission during the day than during the night. On cattle farms, NH₃ concentrations tended to increase slightly during the second-half of the measurement period and to decrease again during the last hour of the measurement period. Such a trend is in agreement with the results reported by Teye *et al.* [12] and Zhang *et al.* [17], who obtained the lowest NH₃ emissions on cattle farms after midnight, probably because of the lower activity level of the cows.

The evolution of NH₃ concentrations on poultry farms was not homogeneous; and yet, NH₃ concentration values tended to increase slightly in the first half of the measurement period, and to decrease in the second half of the measurement

period. The values of daily exposure to NH₃ fell within the range 2.71 - 11.38 ppm, except for the farm with the highest value (FB_01), which consistent with the range of values reported by Whyte [33].

H₂S is the gas with the lowest exposure values, with zero daily exposure in 87% of cases and zero short-term exposure in 84% of cases. Only four farms showed DE values above zero, in descending order: one broiler farm, two pig (fattening and breeding) farms and one dairy farm. The same farms, plus an additional dairy farm, showed short-term exposure values above zero. All the beef cattle farms showed zero values for both types of exposures. These values resulted from nil measurements throughout the day.

The daily evolution of hourly H₂S concentrations on farms with positive exposure values showed an increase in concentrations during the first half of the measurement period, and a decrease during the second half of the measurement period. The farms with the highest exposure values (FP_01 and FB_01) showed two peaks of H₂S concentration, one in the morning and a second in the evening. The poultry farm with the highest H₂S concentration showed the highest NH₃ concentrations, a correlation that is not observed on pig farms. Therefore, the values of exposure to H₂S do not appear to be correlated with the maximum values of exposure to other gases.

In agreement with the results reported by Teye *et al.* [12], exposures to CO₂ were below the exposure limit values. Poultry farms showed the highest values and the largest variations during the measurement period.

During the measurement period, none of the values of daily and short-term exposures to NH₃, H₂S or CO₂ exceeded the ELV, which suggests that the analysed farms had the appropriate exposure conditions for workers and animal welfare during the measurement period. For the assessment of exposure to harmful gases after the measurement period, the Spanish legislation [26] considers the concentration of harmful gases in the environment as a random variable and allows for the use of the IE to assess the acceptability of the exposure.

Figure 1 shows the IEs to NH₃ and CO₂ for all the farms studied, including the limit values. The index of exposure to H₂S has not been included in the figure because the values of the index were above zero on only two farms, and below 0.10 in both cases. The index of exposure to NH₃ was acceptable on 55% of the farms. Cattle farms showed acceptable values of exposure to NH₃ (1 out of 8, 92%), followed by pig farms

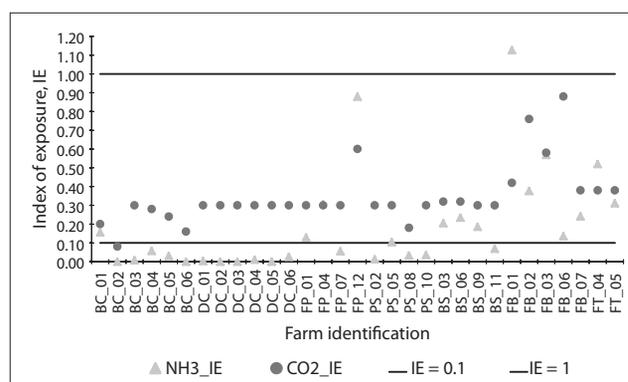


Figure 1. Index of Exposure (IE) to NH₃ and CO₂, including limits defined to determine acceptability of the index. Key: BC – beef cattle; DC – dairy cattle; FP – fattening pigs; PS – pregnant sows; BS – breeding sows and piglets; FB – fattening broilers; FT – fattening turkeys.

(6 out of 12, 50%). For poultry farms, only broiler farm FB_1, the poultry farm with the highest stocking density, had an unacceptable IE to NH_3 . These results support those reported by Rom and Dahl [34] and Miles *et al.* [35], who found a correlation between stocking density and NH_3 emissions.

The indices of exposure to CO_2 show a less clear pattern because the acceptability of the data collected for most farms (98%) cannot be defined. Only one of the beef cattle farms had an acceptable index of exposure to CO_2 . On pig farms, the indices of exposure to CO_2 were more stable than the indices of exposure to NH_3 .

An ANOVA was performed to compare DE, SE and IE, according to the production activity on each farm (cattle, pigs or poultry). Significant differences were found for all the variables except for H_2S . In addition, a *post-hoc* Tukey's HSD test was carried out to specify which groups differed significantly. The test revealed significant differences for DE and IE to NH_3 , and for DE to CO_2 , between broiler farms and beef or dairy cattle farms. In addition, significant differences in DE to CO_2 were found for pregnant and breeding sows. The largest differences between groups were observed for SE to CO_2 , both for 30-min periods, and for the maximum value of CO_2 concentrations, particularly between broiler and cattle farms, and between broiler and pig farms. Actually, the highest value of exposure to NH_3 was found on poultry farms, and the lowest value of exposure to NH_3 on cattle farms. Short-term exposures to NH_3 and CO_2 showed the largest variations between farms.

The same analysis was performed to test the differences between farms according to livestock species. However, no significant differences were found within each group for the parameters studied. Such a lack of variability may suggest that both livestock species and production system or farm type can affect the quality of the air inside the building.

In view of the results for exposures according to type of farming, two indices of stocking density have been used: live weight per unit building area and air volume available per unit live weight. An ANOVA was performed that considered live weight at intervals of 10 kg/m^2 and air volume available per unit live weight at intervals of 50 l/kg . The values of DE and IE to CO_2 showed significant differences between live weights of $0\text{--}10 \text{ kg/m}^2$ and $71\text{--}80 \text{ kg/m}^2$. Again, significant differences were observed for air volume per unit live weight between the indices of exposure to CO_2 . The *post-hoc* Tukey's multiple comparison test revealed significant differences between the $251\text{--}300 \text{ l/kg}$ group and many of the groups below that value. Although the increase in stocking density involved an increase in variability of exposure, the highest exposure values corresponded to the highest stocking densities.

The working period inside the buildings was shorter on poultry farms (4.57 h on average) and longer on cattle farms (7.00 h). Yet, the analysis did not reveal significant differences based on the total hours devoted to farm management activities according to type of farming ($F_{5,25} = 2.021$, $p = 0.110$). Besides, no significant differences emerged from the analysis of the working hours spent inside the building during the morning (between 09:00 - 15:00) ($F_{5,25} = 0.598$, $p = 0.702$). Conversely, significant differences were found when analysing the working hours spent inside the building in the afternoon and evening (between 15:00 - 21:00) ($F_{5,25} = 2.749$; $p = 0.041$).

Figures 2 and 3 show the percentage of farms with activity inside the buildings for each hour during the measurement

period and the evolution of average hourly concentrations of NH_3 and CO_2 for each type of farm. The distribution of the working hours during the day varied with farm type. Farming operations on poultry farms were carried out mainly during the morning (9:00-13:00) and the evening (19:00 - 21:00), which were the times of day with the highest NH_3 concentrations. On the contrary, farming operations on pig and cattle farms were distributed over the whole day, except for the mid-hours of the measurement period.

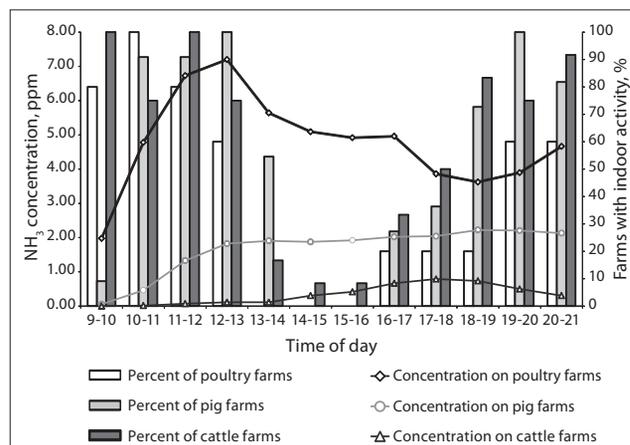


Figure 2. Comparison of percentage of farms with activity inside buildings at every hour, and average hourly NH_3 concentration.

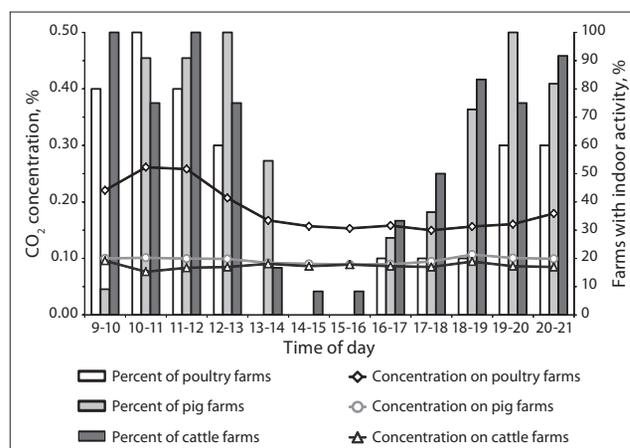


Figure 3. Comparison of percentage of farms with activity inside buildings at every hour, and average hourly CO_2 concentration.

On poultry farms, CO_2 concentrations showed the highest values during the morning, when most farms performed farming activities. Pig and cattle farms showed a more stable trend, with values of CO_2 concentrations below the values recorded for poultry farms.

Analysis of the times of day with indoor activity and the hourly concentrations of gases (NH_3 and CO_2) revealed no significant differences for NH_3 concentrations between hours with indoor activity and hours without indoor activity when the three types of farms were jointly considered. Conversely, significant differences were found for CO_2 concentrations (NH_3 , $F_{1,370} = 0.805$, $p = 0.370$; CO_2 , $F_{1,370} = 4.040$, $p = 0.045$). The comparison of concentrations for all the hours did not reveal significant differences for any of the gases (NH_3 , $F_{11,360} = 1.178$, $p = 0.301$; CO_2 , $F_{11,360} = 0.558$, $p = 0.862$). When analysing the periods with indoor activity in the three types of farms, no significant differences were found (NH_3 ,

$F_{11,188} = 0.855$, $p = 0.586$; CO_2 , $F_{11,188} = 1.297$, $p = 0.229$). The analysis of each separate type of farm revealed no significant differences between hourly concentrations or between the concentrations at periods with indoor activity and the concentrations at periods without indoor activity. However, significant differences were found between the concentrations of both gases on pig breeding farms, depending on the type of activity (NH_3 , $F_{11,36} = 3.280$, $p = 0.003$; CO_2 , $F_{11,36} = 2.364$, $p = 0.026$).

Given the importance of relative humidity and inside air temperature, the correlation of environmental factors with exposure to NH_3 and CO_2 was analysed. The average relative humidity and the average temperature for the analysed period were compared with exposures and indices of exposure. Significant positive correlations were found between average temperature and CO_2 values, and between average relative moisture and the values of NH_3 , CO_2 (except for SE-30') and H_2S_{SE} . However, the R2 values of the linear regressions performed were below 0.300. Other authors have found correlations between environmental variables, such as temperature and gas concentrations. A number of authors have observed an increase in NH_3 concentrations with the increase in temperature in farm buildings [17, 22, 34, 36]. Such a tendency can be explained by the indirect effects of air temperature on NH_3 emissions. Air temperature affects the temperature of the manure surface, affecting the desorption rate [37], urease activity [38], equilibrium between ammonia and ammonium [39], and the gaseous fraction of ammonia [40].

The evolution of average gas concentration, temperature and average relative humidity was analysed at 10-min intervals during the measurement period. The analysis confirmed the tendency observed for the correlation between temperature and NH_3 . For 15 out of the 31 farms studied, the R2 coefficient of the positive linear correlations between NH_3 concentrations and temperature was above 0.5. For cattle farms, two beef cattle farms and three dairy farms obtained zero values of NH_3 concentration in most measurements. As a result, no correlations were observed for such farms. Only two dairy farms and one beef cattle farm showed R2 coefficients above 0.5. The tendency on these farms coincides with the tendency suggested by Zhang *et al.* [17] for dairy housing.

On the contrary, nine out of the 12 pig farms analysed showed R2 coefficients above 0.5. Among these farms, six are pig-fattening farms, three were pregnant sow farms and two were breeding sow farms. The tendency observed for these farms is not in agreement with the exponential pattern described by Jeppsson [22] for a pig-fattening farm. Moreover, only two of the pig farms analysed, EBS_09 and EFP_12, showed values within the range of values obtained by Jeppsson for the correlation coefficient (0.86-0.91). EBS_09 and EFP_12 showed values of 0.85 and 0.89, respectively. The R2 coefficient for poultry farms ranges 0.2 - 0.8 and was above 0.5 on three of the farms.

Analysis of NH_3 concentrations as a function of relative humidity revealed three distinct patterns. In some cases, NH_3 concentrations increased with the increase in relative humidity up to a maximum value, and then decreased again. Maximum concentration values were found for relative humidity values between 60 - 80%, mostly in the range 67% to 71% (Fig. 4). This pattern was observed on eight farms (EBC_05, EBS_06, EA_02, EA_03, EA_05; EFP_01, EA_01;

EA_04), two of which showed a decrease in concentration due to the small range of humidity that characterises the measurements. The second pattern observed showed scattered points, or a scale decrease in NH_3 concentration as a function of relative humidity, with a clear and marked decrease from values of relative humidity between 66-70% for cattle and poultry farms, and between 45-55% for dairy and pig farms (Fig. 5). Finally, the third pattern observed for the correlation between NH_3 concentrations and relative humidity was exclusive to pig farms (EBS_03, EFP_04, EPG_05, EBS_11), with two peak NH_3 concentrations at relative humidity values between 42-56% and 66-70% (Fig. 6).

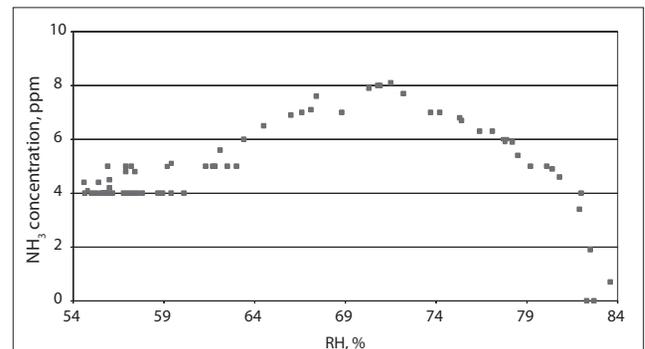


Figure 4. Variation in NH_3 concentrations measured every 10 minutes as a function of relative humidity on farm FB_02.

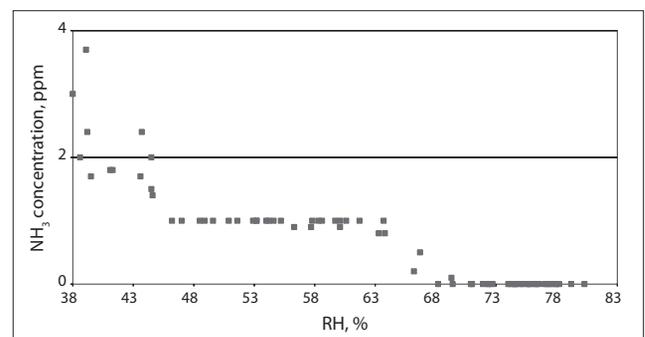


Figure 5. Variation in NH_3 concentrations measured every 10 minutes as a function of relative humidity on farm BC_04.

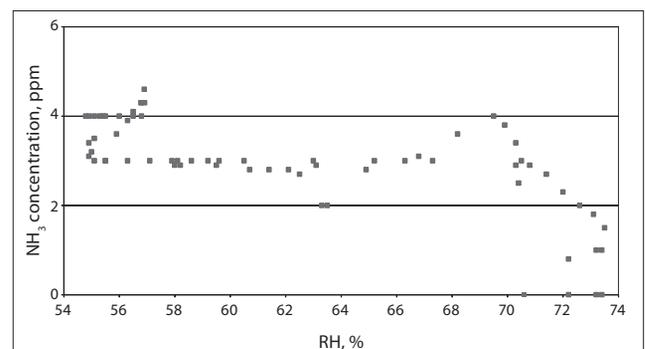


Figure 6. Variation in NH_3 concentrations measured every 10 minutes as a function of relative humidity on farm BS_03.

The common factor of the three patterns described above is the decrease in NH_3 at high humidity levels. High humidity could cause the cake to become anaerobic, diminishing NH_3 emission [41].

CONCLUSIONS

The values of daily exposures and short-term exposures to NH₃, H₂S and CO₂ were below the corresponding exposure limit values in all cases. During the measurement periods, the exposure conditions on the farms were appropriate from the perspectives of occupational hygiene and animal welfare.

Animal species affect the value of exposures to the analysed gases. Significant differences were found for poultry farms. For NH₃ emissions, differences were observed for DE between poultry and cattle farms, with higher values on poultry farms. For CO₂ emissions, differences were found for DE between the three types of farms.

The values of the exposure indices suggest that exposure to H₂S was acceptable in all cases, because H₂S was the gas with the lowest presence on the analysed farms. The acceptability of NH₃ concentration was higher on cattle farms than on pig farms. On poultry farms, some values of exposure to NH₃ were not acceptable. The indices of exposure to CO₂ showed a less clear pattern on the three types of farm.

Stocking density (kg/m²; m³/kg) affected the values of exposure to the analysed gases. Significant differences were found between exposures and exposure indices for CO₂ extreme values.

Analysis of the working hours and average hourly concentration of gases during the times of day with presence of workers inside the farm buildings revealed significant differences for CO₂.

A positive correlation was observed between NH₃ concentration and increase in temperature on most farms. For the relation between NH₃ concentration and relative humidity, three patterns were found:

- 1) an increase in NH₃ concentration up to a point and a subsequent decrease in the concentration;
- 2) scale decreases with the increase in relative humidity;
- 3) two peak values for specific values of relative humidity on farms of some species (pigs).

The common factor was the decrease in NH₃ concentration at high relative humidity values.

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