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Levels of two pollutant gases, temperature, and relative humidity and their influence on broiler welfare

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SUMMARY

Air quality is important for animal welfare, especially for barn-housed broilers. Modern sensors can measure concentrations of pollutant gases such as ammonia (NH_3) and carbon dioxide (CO_2) in short intervals but are not routinely used on broiler farms. This study investigated how fluctuations in climate parameters during individual fattening periods affect broiler welfare under practical conditions. We equipped 2 farms with sensors and recorded NH_3 and CO_2 concentrations, temperature, and relative humidity. To examine relationships between these climate parameters and animal welfare indicators, we assessed body weight, foot pad dermatitis, hock burn, plumage soiling, lesions in the cloacal region, and gait score of the broilers at the end of a fattening period. The results showed that NH_3 concentrations stayed low at the beginning of a fattening period and increased towards slaughter age, whereas CO_2 accumulated at the beginning. Fattening periods with elevated NH_3 concentrations showed altered risks for the occurrence of foot pad dermatitis and hock burn, whereas periods with elevated CO_2 concentrations tended to show altered risks of plumage soiling, foot pad dermatitis, and body weight changes. The study demonstrates that the dynamic of the 2 pollutant gases is complex. They do not have a temporal relationship in their concentration profiles, and therefore, both gases need to be monitored. Continuous monitoring offers valuable insights for improving housing conditions, such as adjusting ventilation strategies. Although a tested automated ventilation adjustment did not reduce gas concentrations, the findings underline the importance of sensor-guided climate control and farm-specific solutions to promote both animal welfare and high air quality standards.

Statement of primary audience

This work is particularly interesting for people who either directly care for broiler flocks and focus on housing climate, such as herd managers or veterinarians who care for livestock, or researchers who are interested in effects of housing climate parameters under practical circumstances.

Description of problem

Animal welfare in farm animal husbandry has been an important topic in Europe and one of growing interest in other countries (Beaumont et al., 2010; Bonafos et al., 2010). In Germany, a member state of the European Union, minimum criteria for the keeping of broilers are stipulated at the national level in the German Order on the Protection of Animals and the Keeping of Production Animals (TierSchNutztV, 2006), which includes provisions on air quality in poultry houses. Ventilation systems in barns with forced ventilation must be operated such that gas concentrations do not exceed 20 ppm for ammonia (NH_3) and 3,000 ppm for carbon dioxide (CO_2) according to the German manual for animal welfare monitoring in livestock farming (Handbuch Tierschutzüberwachung in Nutztierhaltungen, 2025). Furthermore, heat stress must be prevented and excess air moisture discharged by ventilation. However, many air quality parameters are

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not yet routinely and continuously monitored in broiler barns, or ventilation rates lower than needed for an adequate air exchange are used to save energy in regions with cold weather conditions (Corkery et al., 2013; Naseem and King, 2018).

NH_3 is the most studied pollutant gas in farm animal husbandry in general (Ni et al., 2020). It is presumably the most harmful gas produced in poultry housing, so strict monitoring and control are recommended (Naseem and King, 2018). Numerous negative effects on animal health have been described, and they differ depending on gas concentration and duration of exposure. For example, clinical keratoconjunctivitis and uveitis occurred in broilers after a 1-week exposure to concentrations of 50 or 75 ppm, and keratitis occurred in broilers after a 3-week exposure to 25 ppm or a 1-week exposure to 75 ppm (Miles et al., 2004). Concentrations above 75 ppm can lead to reduced body weight and increased mortality (Miles et al., 2004). The formation of NH_3 happens in the litter. Broilers excrete nitrogen compounds, which, depending on litter pH and moisture, are processed chemically and microbially to NH_3, with aerobic microorganisms processing these nitrogen compounds faster than anaerobic ones (Groot Koerkamp, 1994; Liu et al., 2007). The litter moisture increases mainly through excrements of the birds, dripping water from the drinker lines, and condensation water in the barn (Toppel et al., 2019). The production of NH_3 remains low at pH-values below 7 and increases considerably at pH-values above 8 (Blake and Hess, 2001). Besides other enzymes, urease has a key function in the aerobic breakdown and is specific for this reaction (Groot Koerkamp, 1994), with highest activity at a pH-value of 9. Both formation in the litter and release into the barn air are critical processes. Several main factors for the release of NH_3 from litter into the air have been determined, one being the air flow directly on the litter surface. The release creates a gradient along which NH_3 travels based on Fick's law of diffusion from the depth of the litter to the surface (Ni, 1999). The moisture content of the litter can also influence the release of NH_3 into the air. Up to a moisture content of 35.1 %, the release increases with increasing moisture, but above 35.1 %, it decreases despite increasing moisture level (Liu et al., 2007).

Besides NH_3, CO_2 can also form in litter and be released into the barn air (Miles et al., 2004). The more CO_2 is released from it, the higher is the pH-value of the litter (Ni, 1999). However, CO_2 in poultry barns originates mainly from the burning of fuel used for machines or barn installations and from the birds' respiration. The ambient air already contains CO_2 levels amounting to about 300 to 500 ppm at room temperature (Olanrewaju et al., 2008). On day 1 of a fattening period, fuel-operated heaters are likely the main source of CO_2, whereafter the overall CO_2 emissions increase with increasing age of the birds, and at slaughter age, the birds themselves are the main source (McGovern et al., 2001; Knížatová et al., 2010). CO_2 can affect the health of broilers, although McGovern et al. (2001) found no increased mortality rates and no occurrence of ascites in broilers held at 6000 versus 2,500 ppm CO_2. However, Olanrewaju et al. (2008) found that increased CO_2 concentrations of 3,000, 6,000, or 9,000 ppm in comparison with a control level were associated with body weights reduced by 12, 15, and 19 g, respectively, between day 1 and day 14. At 28 and 42 days of age, the body weights no longer differed (Olanrewaju et al., 2008). The onset of unconsciousness has been described after exposure of broilers to 190, 000 ppm CO_2 for 4 min, as determined by the associated loss in body posture (Gerritzen et al., 2007).

In addition to pollutant gases, parameters of the hydrothermal system are also important aspects of the housing environment of broilers. The parameters temperature, relative humidity, air quality, and litter material are closely linked to one another in broiler barns. If one of these parameters is changing, another can be influenced strongly (Lima et al., 2020). Temperature can be explained as the energy of a substance's or body's molecules that move at a certain speed (Caballero, 2014). Birds do not have sweat glands and therefore must regulate their body temperature through breathing and panting. Their body can also be cooled passively through air flow (Aviagen, 2018). High temperatures can lead to heat stress in broilers, which can negatively affect performance, health, growth rates, and well-being of the birds (Altan et al., 2003; Estévez, 2015; Behura et al., 2016; Lima et al., 2020). Heavy broilers especially need low air temperatures (Purswell et al., 2012). Relative humidity is the degree of water saturation in the air at a given temperature (Caballero, 2014). Temperature and relative humidity together influence the well-being of broilers and therefore are potential stress factors for the birds (Behura et al., 2016; Aviagen, 2018). Owing to their lack of sweat glands and their small body surface, broilers seem to be less dependent on relative humidity than other farm animals (Tao and Xin, 2003). Nonetheless, elevated relative humidity can amplify the negative effects of dry-bulb temperature (Tao and Xin, 2003). At constant air pressure, dry-bulb temperature equates to the measured ambient temperature in an environment without air flow. Wet-bulb temperature is the temperature that is reached through the release of energy by evaporation once the ambient air is saturated with water (Caballero, 2014). For homeostasis in birds, dry-bulb temperature has more influence than wet-bulb temperature (Tao and Xin, 2003). Thus, to identify specific risk factors in European broiler husbandry, it is important to assess not just one parameter but to focus on high-quality data from European broiler production and include multivariable effects (van Limbergen et al., 2020).

The objective of the present study was to assess and analyze barn climate data in conventionally managed broiler husbandry and to identify potential correlations with relevant animal welfare indicators from broiler assessments. We here focused on the 2 most frequently occurring potential pollutant gases, NH_3 and CO_2. The analysis included gas concentrations exceeding threshold levels as determined in previous studies. In contrast to previous study designs, which were based on constant exposure levels for determined periods and compared these with control levels, the present study considered the usual fluctuations in pollutant gas concentrations observed in practice. In coordination with the operating barn manager, we additionally examined if an optimized ventilation control setting could help reduce NH_3 and CO_2 concentrations.

Materials and methods

Farms, barns, and animals

The study took place on 2 broiler farms in northern Germany. Both farms housed conventional Ross 308 broilers (Aviagen, Inc., Huntsville, AL), raised them in mixed-sex flocks, and applied the split fattening method. The chicks were from conventional breeders and were delivered on day 0. In each fattening period, a thinning was conducted (day 29 or 30 on farm 1, day 34 or 35 on farm 2) before final depopulation of the barn for slaughter (days 37 to 39 on farm 1, days 40 to 42 on farm 2). Two barns per farm were assessed. The size of each barn was 1,800 m^3 on farm 1 and 1,700 m^3 on farm 2. The target maximum stocking density was 35 kg/m^2 on both farms.

The barns had forced ventilation systems with negative pressure ventilation at the roof ridge via electrically powered radial fans (8 fans per barn on farm 1, 10 fans per barn on farm 2) that directed the air flow outward and with passive inflow of fresh air through ventilation flaps (138 flaps per barn on farm 1, 90 flaps per barn on farm 2) located primarily in the 2 long side walls. The same ventilation system was used on both farms. It had a maximum air exchange capacity of 314,247 m^3/h per barn on farm 1 and of 304,620 m^3/h per barn on farm 2. Heating was provided by a combination of gas cannons installed in the barn and underfloor heating. The entire system was controlled by stored key figures and by daily adjustments made by the staff responsible for the livestock. Adjustments were always made in the same way in both barns of a farm. The ventilation rates were stored based on the calculated ventilation requirements. A detailed overview of the ventilation rates during the individual fattening periods is provided in Supplementary Figure 1.

Before each fattening period, the barns were cleaned, disinfected, and bedded with fresh litter. Farm 1 used straw pellets, farm 2 wood pellets as litter material. The barns on farm 1 had northwest–southeast orientation, those on farm 2 had north–south orientation. As enrichment material, each barn contained 2 rings with 5 pecking stones of differing hardness per ring (2 stones from Crystalyx Products GmbH, Münster, Germany, and 3 from Deutsche Vilomix Tierernährung GmbH, Neuenkirchen-Vörden, Germany), which were replaced as needed.

The climate data stored for each fattening period and the animal data assessed at the end of each fattening period were used for analysis. Climate data were collected for 3 fattening periods on farm 1 and for 10 fattening periods on farm 2. Broiler assessments were made after all 3 fattening periods on farm 1 and after 8 of the 10 fattening periods on farm 2. Details are described in the following subsections. The broiler assessments were not classified as an animal experiment by the ethics committee of the veterinary faculty (Ludwig Maximilian University of Munich, file number 01-11-02-2020) and were therefore approved. Assessments were conducted in accordance with principles and specific guidelines approved by the institutional animal care and use committee (IACUC).

Collection, storage, and computation of barn climate data

Each barn was equipped with 1 CO_2 sensor and 1 NH_3 sensor. The farm managers selected the sensor models to allow for optimal integration into the existing information technology systems in the barns. On farm 1, SKOV sensors were installed, namely, DOL 53 for NH_3 and DOL 19 for CO_2 (SKOV A/S, Glyngøre, Denmark). Farm 2 used a SKOV DOL 53 sensor for NH_3 and an E+E 820 sensor for CO_2 (E+E Elektronik Ges.m.b.H, Engerwitzdorf, Austria). The measurements of temperature and relative humidity were made with SKOV 114 sensors (SKOV A/S, Glyngøre, Denmark) on farm 1 and with FANCOM humidity sensors (FANCOM BV, Panningen, The Netherlands) and SKOV DOL 14 temperature sensors (SKOV A/S, Glyngøre, Denmark) on farm 2. On farm 1, the pollutant gas sensors were installed in the barn center on the sensor board 70 cm above ground. On farm 2, they were installed in the rear barn third 10 cm above the drinker line on the right side (as viewed from the entrance). The absolute height varied because the farm manager adjusted the drinker line according to the body height of the broilers.

The sensors for both gases were specially installed for the project by specialist companies commissioned by the 2 farms. No additional calibration took place apart from the initial adjustment made at the factory during the production process. The SKOV DOL 53 NH_3 sensor is specified by the manufacturer with an accuracy of 1.5 ppm or 10 % of the measured value. It may have a long-term deviation of <10 %, so the sensor should only be used for 3 years. The accuracy of the CO_2 sensors is also specified by both manufacturers. The E+E 820 CO_2 sensor is specified at 25 °C and 1,013 mbar in the used range from 0 to 10,000 ppm with an accuracy of less than 100 ppm plus 5 % of the measured value. The SKOV DOL 19 CO_2 sensor is specified at 25 °C and 1,013 mbar in the range from 0 to 7,000 ppm with an accuracy of 50 ppm plus 5 % of the measured value, and in the range from 7,000 to 10,000 ppm with an accuracy of 100 ppm plus 5 % of the measured value. Sensors for temperature and relative humidity had already been part of the barn equipment before the project and were used by the farms as part of their management processes.

Customary cables connected the sensors with the barn computer (SKOV DOL 539, SKOV A/S, Glyngøre, Denmark, or FANCOM F38, FANCOM BV, Panningen, The Netherlands), which stored the sensor data for relative humidity, temperature, NH_3, and CO_2 in 10-min intervals in an EXCEL worksheet (EXCEL, Microsoft Corporation, Redmond, WA). The first measurement on each day began at 12:00 AM, the last at 11:50 PM, resulting in 144 measurements per fattening day. For analysis, the results were summarized per day by computing the mean values and recording the lowest value as minimum and the highest value as maximum. In addition, threshold concentrations for the 2 gases were defined. Based on Zhou et al. (2020), we used 15, 25, and 35 ppm as threshold concentrations for NH_3 and calculated the number of measurements exceeding these thresholds for each fattening day. We additionally included 20 ppm, the mandatory upper limit for NH_3 in Germany (TierSchNutztV, 2006). For CO_2, we used threshold concentrations of 2,000, 4,000, and 6,000 ppm based on a study of turkey poults by Candido et al. (2018) and added 3,000 ppm, the mandatory upper limit in Germany (TierSchNutztV, 2006). For each fattening day, the percentage of threshold exceedances was calculated as the number of measurements exceeding the corresponding threshold divided by the total number of measurements and multiplied with 100. To analyze the NH_3 and CO_2 data according to seasons, the periods for spring, summer, fall, and winter were assigned based on meteorological classifications. Spring was defined as the period from March 1 to May 31, summer from June 1 to August 31, fall from September 1 to November 30, and winter from December 1 to February 28/29.

Temperature and relative humidity of the barn air were also measured, recorded, and stored by the barn computers. In addition, these 2 parameters were summarized as temperature–humidity index (THI). To calculate the THI, we used the equation developed by Tao and Xin (2003):

$$THI = 0.85\ T_{db} + 0.15\ T_{wb}$$

where T_{db} is the dry-bulb temperature and represents the measured temperature of the barn air in degrees Celsius and T_{wb} is the wet-bulb temperature based on the following equation (Stull, 2011), which included the measured relative humidity (RH) of the barn air:

$$\begin{aligned} T_{wb} = T\,\text{atan}\left[0.151977\ (RH + 8.313659)^{\frac{1}{2}}\right] + \text{atan}(T + RH) \\ - \text{atan}(RH - 1.676331) + 0.00391838\ (RH)^{\frac{3}{2}}\text{atan}(0.023101\ RH) \\ - 4.686035 \end{aligned}$$

Concentrations of the 2 pollutant gases were summarized as mean value of the individual measurements per fattening day, and the mean value of all fattening days up to the day of broiler assessment was analyzed along with the assessment results of the corresponding fattening period. In the same way, exceedances of the determined threshold concentrations of the pollutant gases were summarized per fattening period and analyzed along with the corresponding assessment results.

On-farm broiler assessments

Both farms conducted a thinning before the final depopulation for slaughter. The thinning took place on fattening day 29 or 30 on farm 1 and on fattening day 34 or 35 on farm 2. On farm 1, broiler assessments were made on fattening day 35, 37, or 38 because the broilers were collected for slaughter on fattening day 37, 38, or 39. On farm 2, broiler assessments were made on fattening day 36, 37, 38, or 39, with the fattening period lasting 40 to 42 days. The broilers were assessed in predetermined, fixed barn areas, always after thinning and before depopulation on both farms. During each assessment, one third of the broilers were examined in the front left of the barn, one third in the center, and one third in the rear right. Owing to travel restrictions during the corona pandemic, differing numbers of fattening periods were evaluated on each farm. In a few fattening periods, barn climate data could be recorded by sensors, but the birds could not be examined. On farm 1, 3 fattening periods including broiler assessments were evaluated. Because slaughter dates had been preponed on short notice, fewer than 100 birds per barn were examined in 2 fattening periods. Accordingly, 100 broilers in barn 1 and 67 broilers in barn 2 were examined in fattening period 1, 100 broilers per barn in fattening period 2, and 50 broilers per barn in fattening period 3. On farm 2, 100 broilers per barn were examined in each of 8 fattening periods, and the data were analyzed along with the corresponding barn climate data collected by the sensors. On farm 2, the barn climate parameters were measured in 2 additional fattening periods without broiler assessments.

During the broiler assessments, light intensity in the barn was lowered to 0.1 lx and the assessors wore headlamps (Model 18630, VARTA Consumer Batteries GmbH & Co. KGaA, Ellwangen, Germany). The broilers to be examined were first circled with mobile separation grids (Lubing Maschinenfabrik GmbH & Co. KG, Barnstorf, Germany) to prevent them from escaping and unmixing the group. The assessment of each broiler began with evaluating the walking ability based on the gait score of the Welfare Quality® Assessment Protocol for Poultry (Broilers, Laying Hens) (2009) on a scale from 0 to 5 before the broiler was picked up for further examination. Score 0 indicated a typical, chicken-specific gait with strides. Score 1 meant that a broiler did not stride when walking but did not show visible signs of lameness. A broiler with score 2 showed lameness without clear indication of the affected side of the body. Score 3 indicated unilateral lameness. A broiler with score 4 walked only a few steps and then squatted owing to lameness, and a broiler with score 5 was unable to walk.

Afterwards, the broilers were weighed on a Mettler Toledo ICS425 scale (Mettler Toledo GmbH, Gießen, Germany) and their body weights rounded up to the nearest 10 g. Then, the broilers were picked up, and their legs were assessed for hock burn (HB) and foot pad dermatitis (FPD). The scoring system of Louton et al. (2020) was used to evaluate HB. Score 0 indicated no lesion. Hocks assessed with score 1 had a single, superficial lesion or several superficial or deep lesions up to 0.5 cm in length. Score 2 indicated a deep lesion longer than 0.5 cm up to 1.0 cm or a superficial lesion longer than 0.5 cm. Score 3 indicated a deep lesion longer than 1.0 cm. Score 4 meant that the entire hock was extensively altered. The feet of each broiler were then assessed for FPD according to the scoring system of Piller et al. (2020). Scores 1 to 3 were assigned analogously to the classification of HB and score 4 was defined as a lesion on the foot pad and 1 or more deep lesions on the toe pads.

Furthermore, skin lesions in the cloacal region were recorded. According to the poultry guidelines of the Association for Technology and Structures in Agriculture, the cloacal region was defined as the posteriorly visible skin region surrounding the cloaca (Knierim et al., 2020). For the assessment of lesions in the cloacal region, score 0 indicated that no injuries were found. Score 1 was assigned for unilateral superficial lesions without visible separation of the skin layers and score 2 for bilateral superficial lesions. Score 3 indicated unilateral deep lesions with complete separation of skin layers. In the assessment of plumage soiling, score 0 indicated clean plumage and score 1 minor soiling on the ventral part of the body. If the dorsal part was also affected, the broilers received score 2. Score 3 indicated major plumage soiling. For statistical analysis, the indicators FPD, HB, lesions in the cloacal region, and plumage soiling were summarized binomially, with 0 indicating no deviation and 1 indicating deviation from the physiological state.

Barn climate control test

On farm 2, we additionally conducted a barn climate control test. Barn 1 and barn 2 each had the same basic parameters of ventilation settings. Ventilation was mostly controlled based on the target temperature. In coordination with the farm manager, we changed the barn climate settings during 5 fattening periods in barn 1 as follows. The basic ventilation setting regarding temperature remained unchanged, and the pollutant gas concentrations were added as additional control variables to include the following settings. From day 0 to day 7, the original ventilation setting remained unchanged upon request by the farm manager, who wanted to ensure that the health of the chicks during this sensitive phase would not be compromised by a possible malfunction of the ventilation system. From day 8 to day 28, ventilation power was automatically increased by 5 % if the CO_2 concentration in the barn exceeded the threshold of 3,000 ppm. From day 29 until depopulation, ventilation power was increased by 5 % if the NH_3 concentration exceeded 20 ppm. From day 29 onward, CO_2 concentration could no longer be considered in the setting because the barn computer could include only 1 parameter influencing ventilation power. For comparison, we used data of the concurrent corresponding fattening periods in barn 2, where the original ventilation settings remained unchanged.

Litter moisture and pH

In each fattening period, litter samples were collected after week 1 on fattening day 8 on average (days 6 to 10), after week 2 on fattening day 15 on average (days 14 to 17), and on the day of broiler assessment on average 3 days before slaughter (days 35 to 39) at the end of fattening. During each collection, 3 litter samples were taken at fixed sampling points. As viewed from the entrance, litter from the open litter area was collected in the left front third of the barn at the level of the seventh ventilation flap counted from the transverse wall. The second sample was taken under the drinker line in the middle of the barn. The third sampling point was in the rear right third at the level of the seventh ventilation flap counted from the upper wall under the feeder line. This scheme was applied in the same way on both farms.

The litter samples were placed in plastic bags, vacuum sealed, and transported in an electric cooling box (Dometic Cool Freeze CFX 35, Dometic Germany GmbH, Emstetten, Germany) to the laboratory, where they were stored at 4 °C in a refrigerator. Within 7 days after collection, the samples were processed as described by Toppel et al. (2019). Specifically, 10 g of each sample with a tolerance of 0.01 g was placed in a glass dish to determine the litter moisture. The samples where dried for 24 h at 105 °C in a drying oven (Binder FD 53 Oven, Tuttlingen, Germany) and then weighed. The weight of each sample was determined after 24, 26, and 2 h of drying. If there was a discrepancy between the 3 measurements, the sample was dried for another 20 h and weighed again. To determine the pH, 2 preparations were made from each sample, and the mean value was calculated. For this purpose, 5 g with a tolerance of 0.01 g were weighed in a beaker and 140 g with a tolerance of 1 g of demineralized and filtered water was added. The mixtures were stirred and measured after 30 min by using a pH electrode (WTW inoLab pH7110, WTW GmbH, Weilheim, Germany).

Statistical analysis

In a first step, the barn climate data was processed. The individual measurements of barn climate data were summarized for each fattening day as described in the subsection on collection, storage, and computation of barn climate data. Threshold exceedances of pollutant gas concentrations were assessed and analyzed analogously. To analyze how NH_3 and CO_2 concentrations changed over time, we used generalized additive mixed models for continuous responses (Lin and Zhang, 1999). To flexibly capture nonlinear trends across the fattening days, we modeled the fattening day with thin plate regression splines (Wood, 2003). We also included random intercepts for each barn to account for barn-specific deviations from the overall mean.

To investigate the relationship between exceedances of the threshold concentrations for NH_3 and CO_2, a Pearson correlation analysis was conducted based on the mean values of the 2 gases per individual fattening day. A further analysis was conducted to determine how the effect behaved when the threshold exceedances of the pollutant gases were adjusted by 10 %.

To check a possible seasonal influence on the barn climate data (specifically, on the pollutant gas concentrations), the fattening days were first assigned to the meteorological seasons and then the total number of days for a season, mean value, and standard deviation were assigned. The climate data for the individual fattening days showed a strong temporal trend. To visualize this trend, thin plate regression splines were used within additive regression models for continuous target variables to accurately estimate the respective climate parameters for a fattening day. A numerical calculation of the effects was not possible, so a thin plate regression spline was created for each season, and the data was evaluated by descriptive analysis and comparison of the graphs.

Next, the animal scoring data was prepared for analysis. The scoring variables HB, FPD, lesions in the cloacal region, and plumage soiling, originally assessed on ordinal scales, were summarized as binomial variables (0 = no deviation from the physiological state or 1 = deviation from the physiological state) because individual degrees of severity were sparse and thus could have confounded models for ordinal data. Based on the resulting mean values per fattening day, the arithmetic mean of each barn climate variable from the barn climate data was computed for each fattening period to analyze relations between barn climate data and broiler assessment results (i.e., body weights and scoring data). For this analysis, we considered only the period of fattening days preceding the corresponding broiler assessment day because the climate data collected afterwards could not have influenced the assessment results.

These data (animal scoring and barn climate) were analyzed with logistic regression models for binomial outcome variables. Fattening period was included as random effect for the intercept. Results are presented as risk ratios (RR). Considering a change in barn climate in relation to a scoring variable, an RR greater than 1 indicates that a certain score can be expected to occur more frequently, whereas an RR less than 1 indicates a reduced relative risk. The RR was used instead of the odds ratio because the RR provides a more intuitive interpretation as the direct ratio of 2 probabilities. In contrast, in our practical experience, the odds ratio is often misinterpreted as a risk ratio. Corresponding 95 % confidence intervals (CI) and 2-sided *p*-values were calculated. Body weight and gait score were considered as continuous outcome variables and analyzed with mixed linear models. These models included the barn climate parameter of interest as fixed effect and barn information as random effects for the intercept. All analyses were conducted with R statistical programming language (R version 4.1.2; R Core Team, 2021).

Observer agreement

In February 2020, inter-observer reliability between the 5 assessors was tested on $n = 100$ broilers. The same 100 broilers were separately assessed by each person. The gait of each broiler was observed together and then evaluated individually. To analyze agreement between the assessors, the prevalence- and bias-adjusted kappa (PABAK) value was computed for each scoring variable. We used PABAK instead of normal kappa because the former is less influenced than the latter by the prevalence of each degree of severity of the assessed variable (Chen et al., 2009). Complete observer agreement would correspond to a PABAK value of 1.0.

Results and discussion

In the present study, altered NH_3 concentrations during the fattening period (i.e., concentrations deviating from the computed mean of all fattening periods) were significantly correlated with altered risks of HB and FPD, and altered CO_2 concentrations with altered risks of FPD, plumage soiling, and body weight changes. There was no direct correlation between elevated NH_3 concentrations and elevated CO_2 concentrations because they did not occur at the same time.

Observer agreement

The PABAK test showed that inter-observer reliability was moderate (defined as the PABAK value ranging from 0.41 to 0.60) for the gait score (0.60) and very good (0.81 to 0.92) for HB (0.82), FPD (0.92), and phenotypic sex (0.92). Inter-observer reliability was excellent (0.93 to 0.99) for plumage soiling (0.93) and lesions in the cloacal region (0.93).

Animal data

We assessed 2,017 broilers, 417 on farm 1 and 1,600 on farm 2. Phenotypically, 45.7 % were female and 54.3 % male, with the percentage differing by 0.5 percentage points between the 2 farms. The average body weight of the broilers on farm 1 was 2,460 g (male broilers 2,395 g, female broilers 2,071 g) and 2,360 g on farm 2 (male broilers 2,522 g, female broilers 2,165 g), corresponding to a total average of 2,410 g on both farms as assessed on fattening day 37.5 (averaged). Table 1 shows an overview of the summarized results for all assessed broilers included in the statistical analysis, presented as binomial variables (except for gait score).

Barn climate data and broiler assessment results

Ammonia. Concentrations of NH_3 in the barn air showed a clear pattern throughout the individual fattening periods. Fig. 1 shows the estimated trend for the minimum, mean, and maximum concentrations on the individual fattening days of all fattening periods and both farms. The trend was similar among all fattening periods.

The concentration in the barn air remained low at the beginning and started rising around fattening day 15. The tendency for increasing NH_3 concentrations around fattening day 15 was similar on both farms and in all assessed fattening periods. At the beginning of fattening, the concentration remained low, as also reported by Adler et al. (2021). It typically increased with the age of the broilers toward the end of the fattening period (Redwine et al., 2002). Atapattu et al. (2017) found an increase in NH_3 concentration after the first fattening week. Louton et al. (2018) found similar trends throughout the fattening period, with higher NH_3 concentration measured on day 39 than on day 5. We first detected concentrations exceeding the thresholds (15, 20, 25, 35 ppm) around fattening day 30. The summarized exceedance frequencies are presented as estimated trends in Fig. 2.

Low NH_3 concentrations at the beginning of fattening in general could result from management practices: Before each fattening period, the barn floors were bedded with fresh, dry litter material and the barns were pre-heated, providing for dry conditions. The formation of NH_3 depends not only on the pH-value but also on the presence of moisture. Knížatová et al. (2010) assumed an elevated enzymatic activity in the litter during the later part of the fattening period, indicated by an increase in litter temperature with concurrent decrease in air temperature

Table 1
Overview of the broiler assessment results on the 2 farms, with score 0 indicating the physiological state without alterations and score 1 indicating a non-physiological state regardless of degree of severity except for the gait score (scores 1 to 5 indicating increasing degrees of severity).

Scoring variable	Score	Farm 1		Farm 2	
		Barn 1	Barn 2	Barn 1	Barn 2
Gait score	0	10.4 %	4.8 %	33.0 %	29.8 %
	1	34.0 %	19.8 %	35.8 %	37.5 %
	2	32.8 %	39.5 %	23.1 %	24.8 %
	3	18.4 %	23.4 %	7.9 %	6.5 %
	4	3.2 %	7.2 %	0.1 %	0.8 %
	5	1.2 %	5.4 %	0.1 %	0.8 %
Foot pad dermatitis (left, right)	0	25.2 %, 25.6 %	41.9 %, 43.1 %	84.5 %, 83.6 %	82.8 %, 82.5 %
	1	74.8 %, 74.4 %	58.1 %, 56.9 %	15.5 %, 16.4 %	17.2 %, 17.5 %
Hock burn (left, right)	0	54.4 %, 48.4 %	47.9 %, 41.9 %	92.1 %, 93.4 %	92.6 %, 92.9 %
	1	45.6 %, 51.6 %	52.1 %, 58.1 %	7.9 %, 6.6 %	7.4 %, 7.1 %
Lesions in the cloacal region	0	26.8 %	13.8 %	19.6 %	21.6 %
	1	73.2 %	86.2 %	80.4 %	78.4 %
Plumage soiling	0	38.8 %	32.9 %	96.0 %	88.0 %
	1	61.2 %	77.1 %	4.0 %	12.0 %

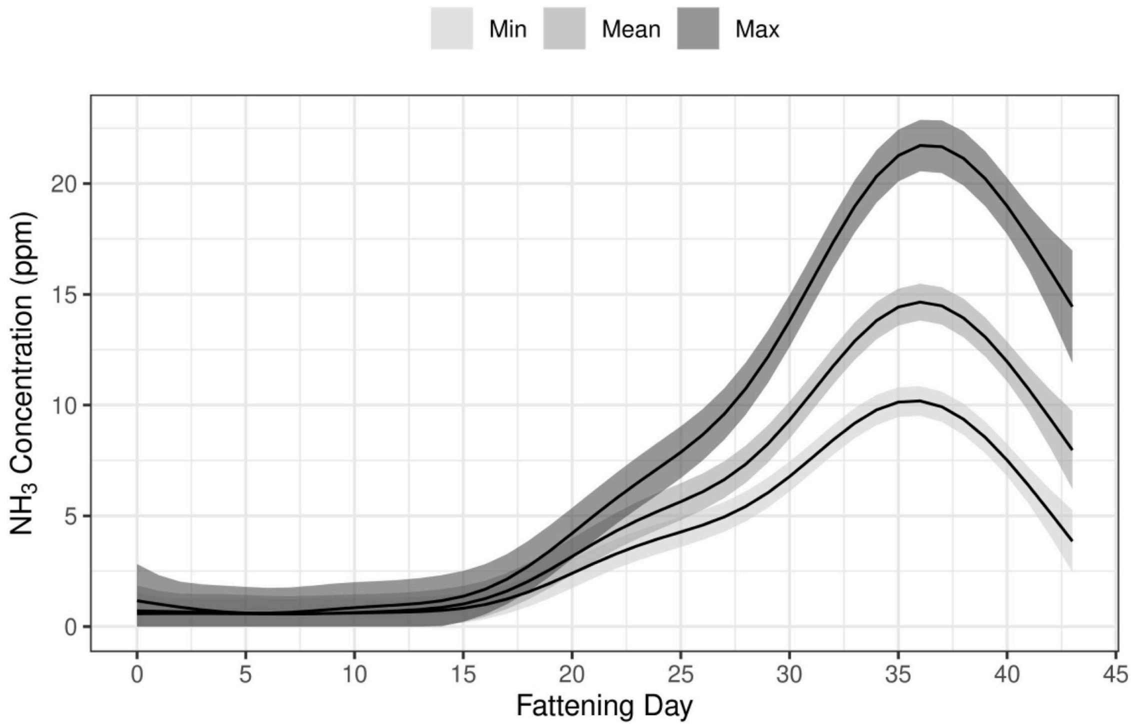

Fig. 1. Estimated curves predicting the NH_3 concentration per fattening day including measurements from all fattening periods on both farms.

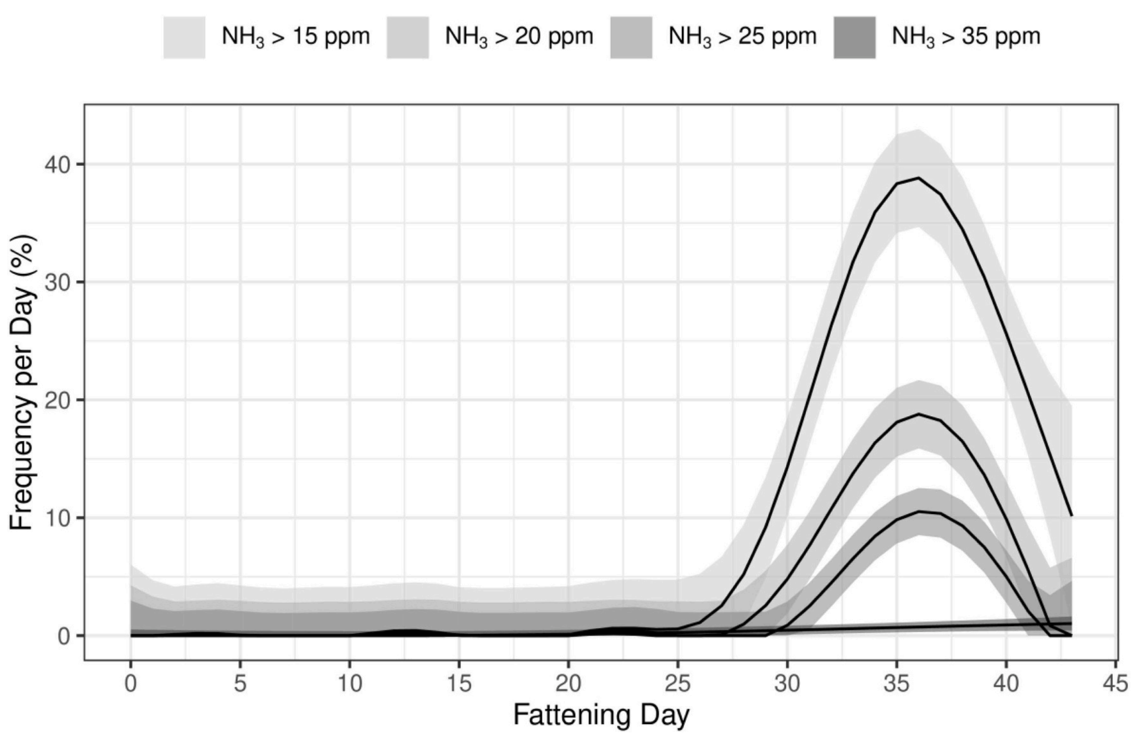

Fig. 2. Estimated curves predicting the exceedance of NH_3 threshold concentrations per fattening day, given as percentage of the measurements made on that fattening day. The model included measurements from all fattening periods on both farms.

in their study. Paradoxically, the decrease in NH_3 concentration at the very end of a fattening period could also be due to increasing moisture in the litter. Liu et al. (2007) reported that a litter moisture level of above 35.1 % can lead to decreasing NH_3 concentrations. According to Miles et al. (2011), this critical percentage can vary depending on temperature. Highest NH_3 concentrations and threshold exceedances occurred around fattening days 35 to 38 in our study, and the highest measured NH_3 concentration was 47.1 ppm. Furthermore, the mandatory upper limit of 20 ppm NH_3 was frequently exceeded during the last third of the fattening periods on both farms. Without continuous measurements, the farmers would not have noticed.

Ammonia and Broiler Assessments. The NH_3 concentrations were analyzed per fattening period and in relation to the results of the corresponding broiler assessments. To do so, we summarized the measured

NH_3 concentrations up to the day of broiler assessment. The subsequent measurements were not considered because they could not have influenced the assessment results.

Mean Ammonia Concentrations and Broiler Assessment Results. The overall mean NH_3 concentration for all fattening periods was 4.7 ppm with a standard deviation (SD) of 1.5 ppm. A deviation from this mean concentration in individual fattening periods could lead to significant changes in the risk of a score greater than 0 for certain scoring variables. Based on the present data, an increase of 1 ppm in the mean NH_3 concentration in a fattening period led to a 15 % higher risk of HB on the right and left legs with an RR of 1.15 (right: 95 % CI = [1.01; 1.30]; p = 0.035; left: 95 % CI = [1.04; 1.26]; p = 0.006).

Ammonia Threshold Exceedances and Broiler Assessment Results. Analysis of the frequency of measurements in which NH_3 concentrations exceeded the predefined thresholds (15, 20, 25, 35 ppm) per fattening period revealed further statistically significant effects. Averaged for all fattening periods, 7 % (SD 7 %) of the measurements in a fattening period exceeded 15 ppm, 3 % (SD 5 %) exceeded 20 ppm, 1 % (SD 1 %) exceeded 25 ppm, and 0.08 % (SD 0.23 %) exceeded 35 ppm. Considering measurements above 20 ppm and 35 ppm, changes in these threshold exceedances were related to significant changes in the risk of FPD during the corresponding fattening period. When the number of measurements above 20 ppm in a fattening period increased by 1 %, the RR for FPD on the left foot decreased by 95 % to 0.05 (95 % CI = [0; 0.94]; p = 0.046). The same trend was found for the right foot with an RR of 0.22 (95 % CI = [0.03; 1.76]), albeit not statistically significant (p = 0.155). We found similar results for the threshold of 35 ppm. An increase of 0.1 % in the number of measurements above 35 ppm per fattening period led to a lower RR (0.74) for FPD on the right leg (95 % CI = [0.29; 0.82]; p = 0.007). The same trend was found for FPD on the left foot with an RR of 0.74 (95 % CI = [0.54; 1.02]), albeit not statistically significant (p = 0.062). The occurrence of FPD and HB differed between the 2 farms. The health and performance of broilers often depend on multiple farm- and housing-specific factors (van Limbergen et al., 2020). Moisture in the litter is one of the main causes of the development of FPD (Toppel et al., 2019) and in combination with age also of HB (Hepworth et al., 2010; Toppel et al., 2019). The type of litter material can also influence foot pad health in broilers. For example, straw pellets can lead to better foot pad health than chopped straw or wood shavings (Berk, 2007). We know of no study in which wood pellets were compared with straw pellets in the same study. In our study, one farm used wood pellets, the other straw pellets. In general, different litter materials have different water holding capacities owing to their physical structure, particle size, and level of compression (Garcês et al., 2013). Moisture is positively correlated with NH_3 concentration (Miles et al., 2004; Liu et al., 2007). One reason for significant, positive correlations between mean NH_3 concentration and HB may be the moisture level in the litter. Regarding threshold concentrations in our study, exceedances of 20 and 35 ppm NH_3 were negatively correlated with the occurrence of FPD, with the left leg affected when the 20-ppm threshold was exceeded and the right leg affected when the 35-ppm threshold was exceeded. These effects were significant but not strong and should be further examined with a larger data set. We can only speculate why the occurrences of HB and FPD differed between left and right legs. Although da Silva Fernandes et al. (2012) found differing lengths of tibia and femur between the left and right legs during the growth period, we do not know to what extent such differences might influence assessment results.

Carbon Dioxide. We found a strong temporal trend for the course of CO_2 concentration during the fattening periods. In contrast to NH_3, the CO_2 concentration tended to be elevated at the beginning of a fattening period. The high CO_2 concentrations at the beginning of fattening could be due to the technical equipment in the barn. Corkery et al. (2013), for example, found a lower CO_2 level in a facility with a heat exchanger system than in one with a conventional heating system, and possibly, less ventilation in the latter caused exhaust gases to be trapped in the barn during the first days (Knížatová et al., 2010). The main source of CO_2 in broiler barns are the heaters and later in the fattening period the birds because of respiration (McGovern et al., 2001). The production of animal-derived CO_2 is mainly influenced by activity, animal species, and food intake (Pedersen and Sällvik, 2002).

Especially on farm 2, high concentrations were measured on the first fattening days, as depicted in Fig. 3, which displays the minimum, mean, and maximum measured concentrations as estimated trend curves. Exceedances of the threshold concentration of 2,000 ppm were rather inconsistent between the fattening periods, as illustrated in Fig. 4 by the CI around the regression line being wider than those computed for the other threshold concentrations. Exceedances of 3,000 and 4,000 ppm occurred especially at the beginning of a fattening period. The curve for 6,000 ppm is without amplitude because this threshold was not exceeded (Fig. 4). Forty-five years ago, such high concentrations were common in broiler production (Reece and Lott, 1980).

The overall mean of the daily mean concentrations in the individual fattening periods ranged from 1,432 to 2,949 ppm. The highest measured CO_2 concentration was 5017 ppm. Our results show that CO_2 concentrations exceeded the mandatory upper limit of 3,000 ppm in practice. Knížatová et al. (2010) also reported exceedance of the mandatory upper limit in all assessed fattening periods. The barns on farms 1 and 2 in our study were equipped with 2 different CO_2 sensors because we conducted a practical trial on conventional farms and thus had to find the fitting sensor for the existing digital barn systems. Like all sensors, these sensors have a certain percentage of measurement error in terms of accuracy. However, we present practical data that can provide valuable incentives to verify the findings through basic research in a test setting.

Carbon Dioxide and Broiler Assessments. Analogous to the analysis of NH_3, the relation between CO_2 concentrations and broiler assessment results was analyzed at the level of the fattening periods.

Mean Carbon Dioxide Concentrations and Broiler Assessment Results. The overall mean CO_2 concentration for all fattening periods was 2,110 ppm (SD 503 ppm). A computed increase of 1,000 ppm in the mean concentration led to significant changes in the risks of body weight changes, FPD right and left, and plumage soiling. Such an increase was associated with a decrease of 20 % in the RR for FPD on the left leg to 0.80 (95 % CI = [0.66; 0,96]; p = 0.017) and, similarly, with a decrease of 22 % in the RR for FPD on the right leg to 0.78 (95 % CI = [0.66; 0.93]; p = 0.004). For plumage soiling, the RR increased to 1.47 (95 % CI = [1.05; 2.05]; p = 0.025) with a 1,000 ppm higher mean CO_2 concentration per fattening period. The body weight increased by 186.04 g (95 % CI = [91.33 g; 289.75 g]; $p < 0.001$) with an increase of 1,000 ppm in the mean CO_2 concentration.

Carbon Dioxide Threshold Exceedances and Broiler Assessment Results. On average, the threshold concentration of 2,000 ppm was exceeded in 56 % (SD 36 %) of the measurements during a fattening period, the threshold of 3,000 ppm in 8 % (SD 13 %), and the threshold of 4,000 ppm in 2 % (SD 2 %). Exceedances of the 2,000-ppm threshold were related to changes in body weight in that a computed increase in the frequency of threshold exceedances by 10 % was associated with an increase in body weight by 29.23 g (95 % CI = [16.13 g; 42.33 g]; $p <$ 0.001). Changes in the frequency of threshold exceedances for 3,000 and 4,000 ppm had no statistically significant effects, and 6,000 ppm were not exceeded in this study.

Assessed Welfare Indicators without Correlation to Pollutant Gas Concentrations. Our study revealed no statistically significant correlation between gait score and pollutant gas concentrations. The gait score has been used in various studies with various levels of grading, and the results varied greatly (Cordeiro et al., 2009). The PABAK value for the gait score in our study showed only moderate observer agreement. We point out that all assessed scoring variables except for the gait score (levels 0 to 5) were analyzed as binomial variables. Van Hertem et al. (2018) reported that a camera-based analysis of flock behavior can be used to draw conclusions about the gait score but not about HB and FPD. The

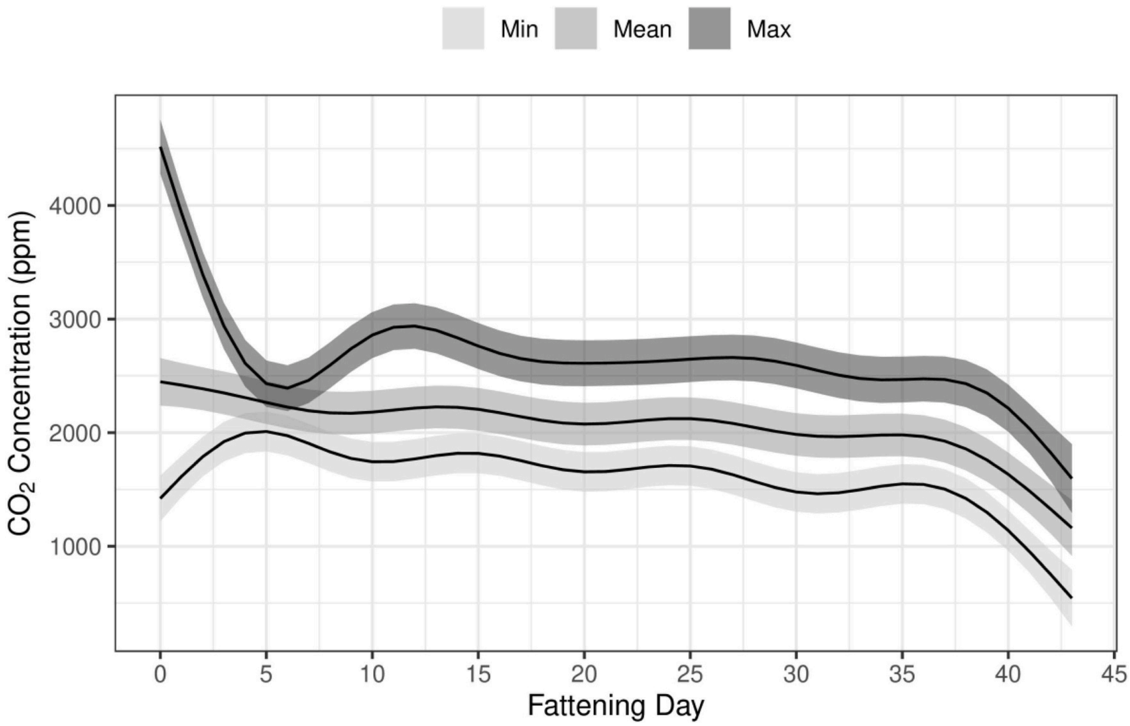

Fig. 3. Estimated curves predicting the CO_2 concentration per fattening day including measurements from all fattening periods on both farms.

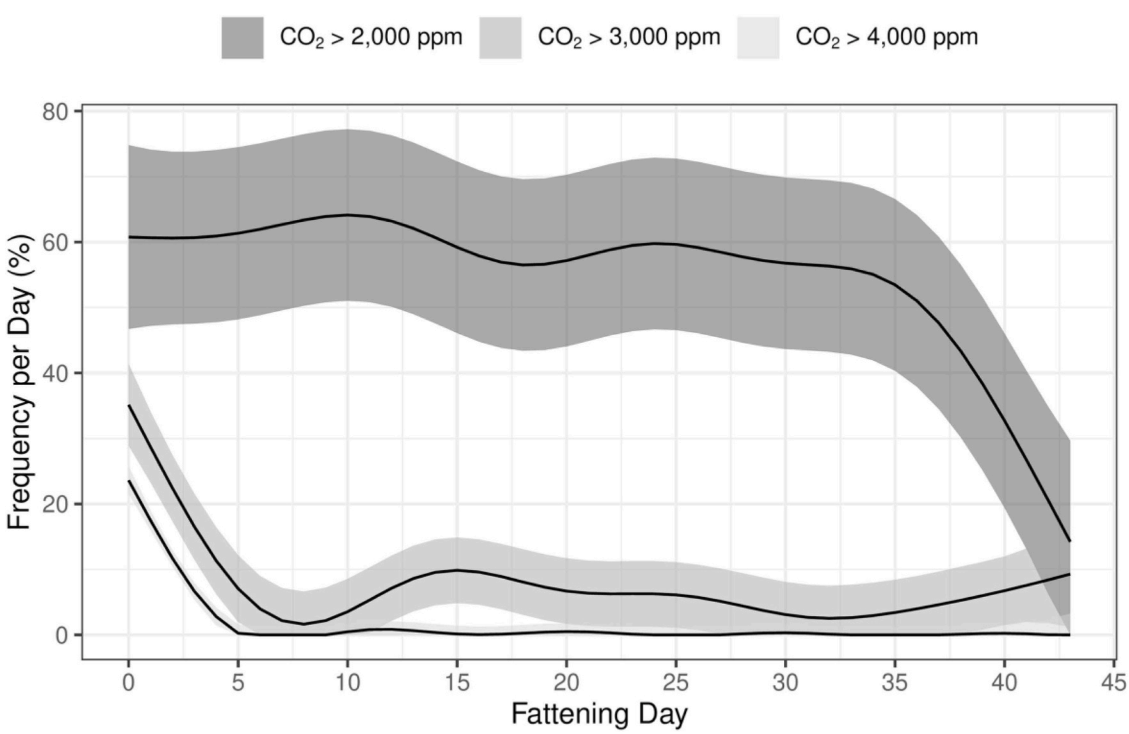

Fig. 4. Estimated curves predicting the exceedance of CO_2 threshold concentrations per fattening day, given as percentage of the measurements made on that fattening day. The model included measurements from all fattening periods on both farms. The confidence interval around the regression line for exceedance of 2000 ppm is wider than those for 3000 and 4000 ppm owing to less consistent exceedance between the individual fattening periods. The 6000-ppm threshold was not exceeded in this study.

data of da Silva Fernandes et al. (2012) indicate only a minor correlation between the differing lengths of left and right femur or tibia and a higher gait score. We found no statistically significant changes in the risk of lesions in the cloacal region in relation to the pollutant gas concentrations.

Correlation Between Ammonia and Carbon Dioxide. To find out if CO_2 concentration could be used as “ventilation equivalent” to predict increased NH_3 concentrations, we conducted a correlation analysis to determine if measurements below the threshold of 20 ppm NH_3 occurred simultaneously with measurements below the threshold of 3,000 ppm

CO_2. The analysis revealed a Pearson correlation coefficient of −0.06 (95 % CI = [−0.12; 0]) for the simultaneous occurrence of concentrations below these thresholds without statistical significance ($p = 0.066$). The adjusted effect considering fattening period–specific influences in computing a change in concentration by 10 % for NH_3 was −0.0008 (95 % CI = [−0.006; 0.0044]) without statistical significance ($p = 0.762$). We found elevated CO_2 concentrations at the beginning and elevated NH_3 concentrations at the end of the fattening periods, with no statistically significant correlation between NH_3 and CO_2. Thus, CO_2 as a "ventilation equivalent" should not be used as an indicator of NH_3-free barn air. Louton et al. (2018) also found no correlation between NH_3 and CO_2 measurements.

Seasonality of Ammonia and Carbon Dioxide. The barn climate data was further analyzed to determine whether the occurrence of pollutant gases was subject to seasonal fluctuations. The concentration profiles and threshold exceedances for CO_2 showed no significant differences between the seasons. Regarding NH_3, no statistically significant difference in the mean concentration values was apparent. However, we found differences in the threshold values, with exceedances of 25 and 35 ppm NH_3 occurring mainly in spring. The effects of the analysis are small because only a few fattening periods per season were included in the study, and seasons overlapped in several fattening periods. Therefore, the results should be interpreted with caution. A graphical assignment of the meteorological seasons to the fattening periods is shown in Supplementary Figure 2.

Temperature, Relative Humidity, and Temperature–Humidity Index. The data are illustrated as estimated concentration curves (Figs. 5–7). The ambient barn temperature decreased continuously from the beginning to the end of the fattening period. The CI around the regression line is very narrow, meaning that the measurements showed little variation among the assessed fattening periods (Fig. 5). Relative humidity during the individual fattening periods tended to increase during the first week and remained at an elevated level until the end (Fig. 6). The THI also showed an obvious trend, similar to that of temperature, among all fattening periods (Fig. 7).

The THI considers the effects of temperature and relative humidity because their effects intensify each other (Kang et al., 2020). The evident strong similarity of our estimated curves for THI and temperature is due to the applied equation weights, which were higher for temperature than for relative humidity. We can assume that the measured levels of temperature and relative humidity and the THI in the individual fattening periods were very similar because each 95 % CI of the thin plate regression splines is very narrow.

Barn climate control test

On farm 2, the basic control setting of the ventilation system in barn 1 was extended to include the pollutant gas concentration during 5 fattening periods and was compared with the setting in barn 2, which had the same basic setting without influence of pollutant gas concentrations. We found no statistically significant difference in NH_3 or CO_2 concentration between the barns. However, as shown in our analyses, elevated pollutant gas concentrations and thus altered climate conditions in the barn can be associated with altered risks for findings from the broiler assessments. The reduction in pollutant gas concentrations is therefore a key contribution to improving the housing environment. Thus, the current ventilation methods should be reconsidered and adjusted. Our tested ventilation increase had no effect and was probably too low.

Litter moisture and pH

The results of our litter analyses are presented descriptively in Table 2. Owing to travel restrictions imposed by the coronavirus pandemic, litter sampling could be completed in only 2 fattening periods on farm 1 and in 7 fattening periods on farm 2. The moisture levels of the litter samples differed greatly between the 3 sampling points in a given barn. Litter from the sampling point under the drinker line was usually more humid than litter from underneath the feeder line or from the open litter area. This could be because the broilers splash water on the floor when they drink.

In addition, the moisture levels measured on the same sampling days

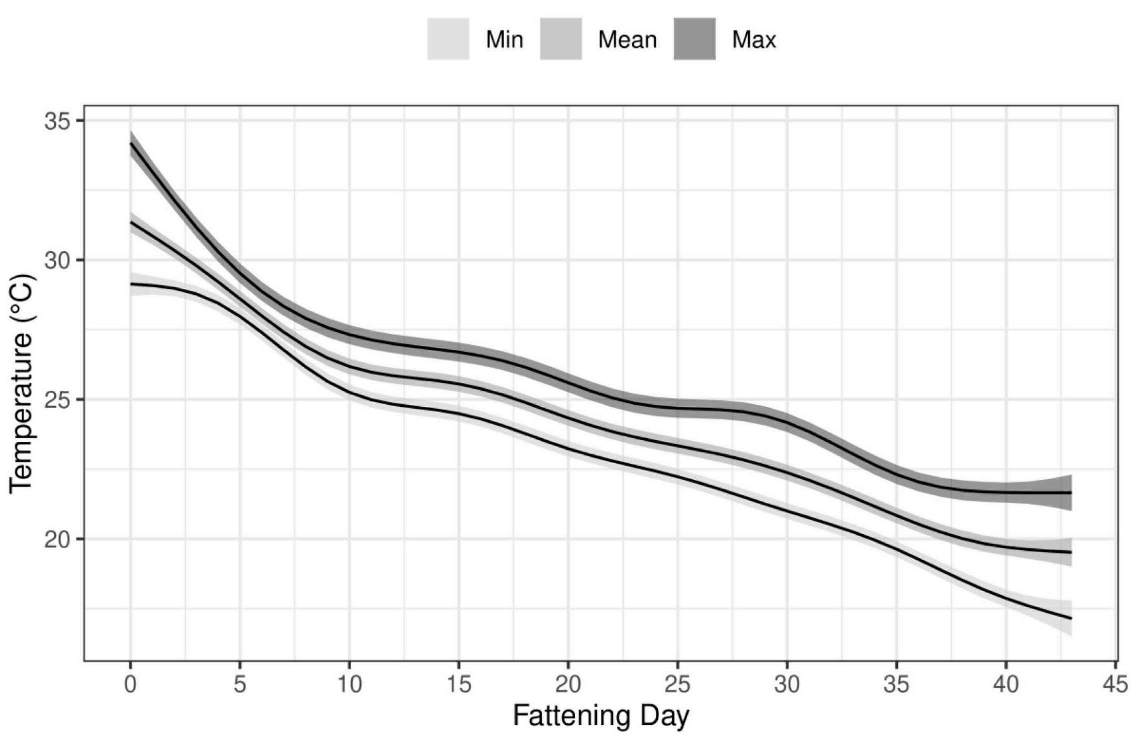

Fig. 5. Estimated curves predicting the ambient barn temperature per fattening day including measurements from all fattening periods on both farms. The narrow confidence intervals indicate little variation between the fattening periods.

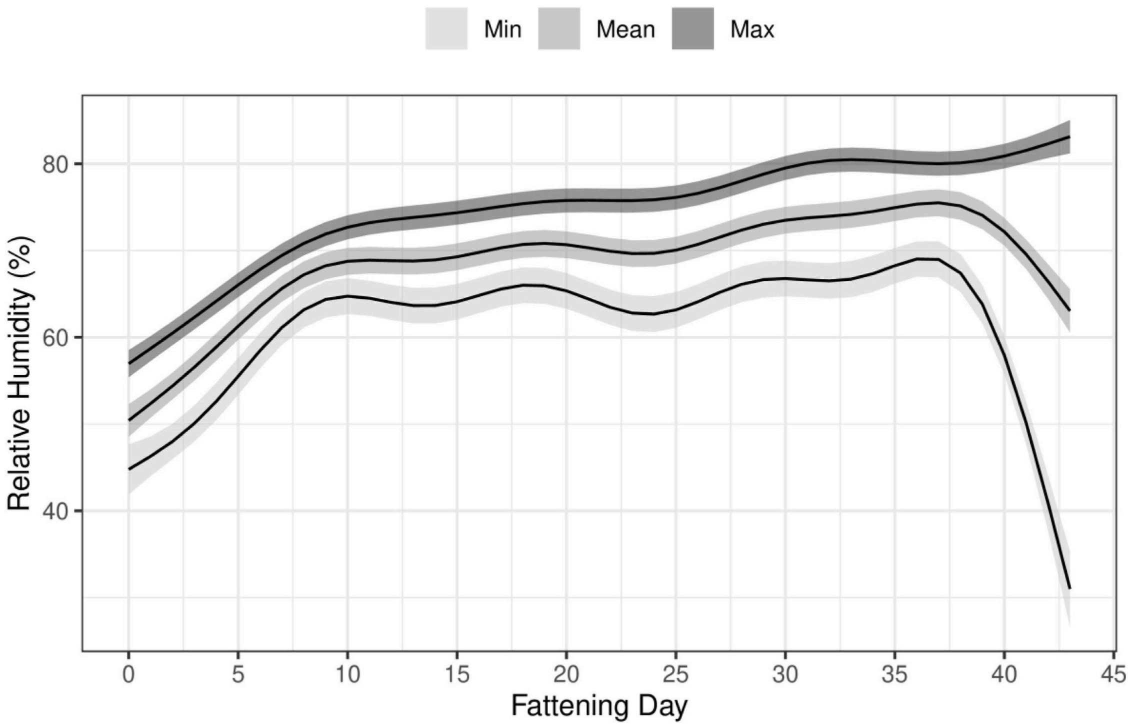

Fig. 6. Estimated curves predicting the relative humidity per fattening day including measurements from all fattening periods on both farms.

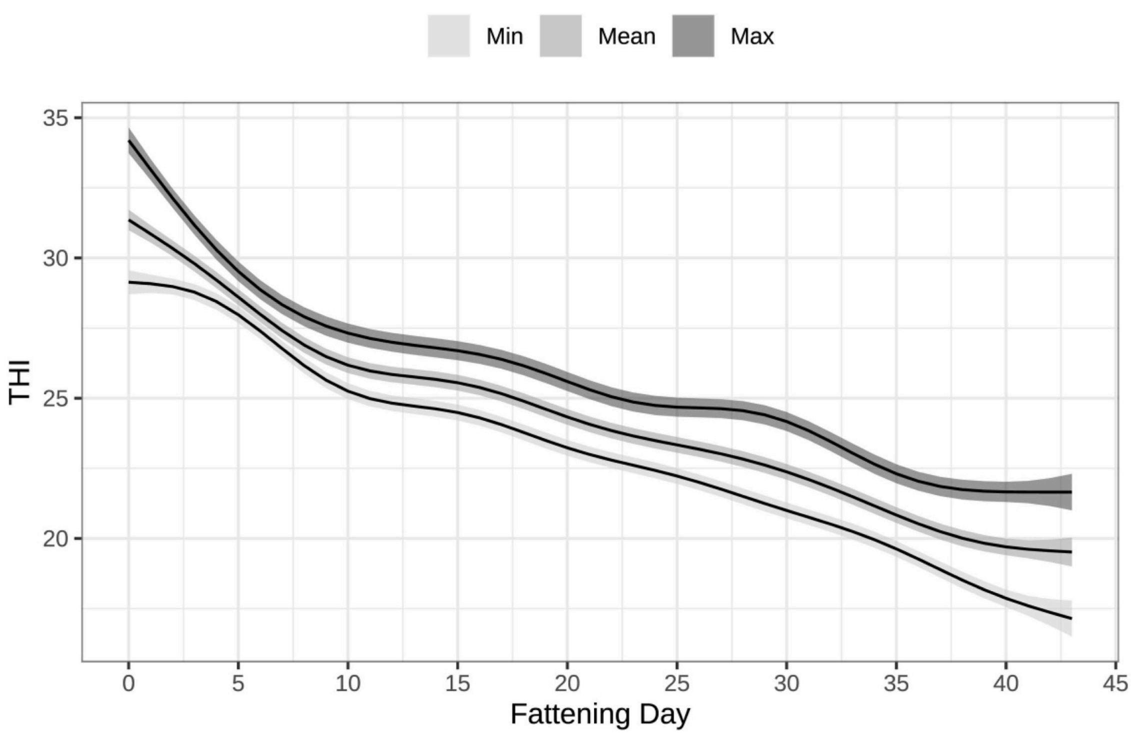

Fig. 7. Estimated curves predicting the temperature–humidity index (THI) per fattening day including measurements from all fattening periods on both farms.

in the same barn were highly heterogeneous. In extreme cases, there were deviations of more than 30 % between the individual sampling locations. It is not possible to say how long the broilers were in contact with wet or dry litter because both were present in the barn at the same time. An interpretation in relation to NH_3 is also complex here, as the results are only available for 3 fattening days per period and only for 3 locations in the barn. Nonetheless, we can derive important information: High moisture levels are often reached in the area underneath the drinkers. This situation should be counteracted by appropriate management measures such as drinkers that are ideally adjusted to the height of the birds or optimized litter management. Both farms had drip trays installed under the nipple drinkers, but these trays apparently could not prevent elevated moisture levels.

Early in the fattening period (day 8), the pH value in the litter was on

Table 2
Moisture and pH of litter sampled in 3 areas of the barn (O = open litter, D = drinker line, F = feeder line) on 3 sampling days throughout the fattening period (measurement 1 = fattening day 8 on average [days 6 to 10], measurement 2 = fattening day 15 [14 to 17], measurement 3 = 3 days before slaughter on fattening days 35 to 39 depending on the length of the fattening period; n. a. = not assessed).

Farm	Fattening period	Barn	Parameter	Measurement 1			Measurement 2			Measurement 3		
				O	D	F	O	D	F	O	D	F
1	1	1	moisture	22.0 %	17.2 %	21.3 %	22.4 %	29.8 %	15.9 %	n. a.	n. a.	n. a.
			pH	7.2	7.6	6.9	6.7	6.3	6.4	n. a.	n. a.	n. a.
		2	moisture	18.0 %	18.2 %	15.5 %	22.7 %	29.0 %	18.0 %	n. a.	n. a.	n. a.
			pH	6.9	7.2	7.0	6.5	6.4	6.8	n. a.	n. a.	n. a.
	2	1	moisture	19.6 %	18.9 %	20.9 %	30.0 %	38.1 %	34.1 %	41.8 %	51.6 %	30.1 %
			pH	6.7	6.6	6.7	6.2	5.8	6.5	9.1	5.4	6.7
		2	moisture	18.0 %	9.0 %	16.6 %	27.4 %	16.3 %	17.0 %	45.2 %	52.0 %	25.8 %
			pH	6.9	6.7	6.7	6.4	6.7	6.7	8.3	5.2	7.1
	3	1	moisture	19.3 %	18.9 %	21.5 %	24.9 %	36.5 %	18.8 %	43.4 %	50.3 %	27.7 %
			pH	7.1	7.1	7.1	6.5	6.5	6.8	8.7	5.5	6.7
		2	moisture	27.6 %	22.9 %	24.6 %	25.4 %	46.4 %	18.7 %	32.5 %	43.0 %	23.2 %
			pH	6.6	6.5	6.5	6.6	6.2	6.9	9.0	5.6	7.0
2	1	1	moisture	14.6 %	27.6 %	16.5 %	24.0 %	35.2 %	28.0 %	n. a.	n. a.	n. a.
			pH	5.8	5.9	5.4	6.0	5.5	5.9	n. a.	n. a.	n. a.
		2	moisture	15.6 %	25.1 %	15.9 %	26.5 %	36.3 %	22.3 %	n. a.	n. a.	n. a.
			pH	5.7	5.8	5.7	6.5	6.8	5.8	n. a.	n. a.	n. a.
	2	1	moisture	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.
			pH	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.
		2	moisture	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.
			pH	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.
	3	1	moisture	13.2 %	19.5 %	14.0 %	21.0 %	23.9 %	17.6 %	28.8 %	29.4 %	21.8 %
			pH	5.5	5.7	5.7	6.7	6.1	6.6	8.8	8.8	8.1
		2	moisture	15.3 %	21.3 %	15.1 %	22.4 %	28.5 %	17.3 %	28.9 %	33.4 %	20.2 %
			pH	5.7	5.9	5.6	6.8	6.4	6.4	8.8	8.8	7.8
	4	1	moisture	17.7 %	23.7 %	14.9 %	28.0 %	25.3 %	19.4 %	33.5 %	27.4 %	17.9 %
			pH	6.1	6.0	6.3	6.1	6.1	6.3	9.0	8.3	7.7
		2	moisture	19.1 %	21.4 %	15.9 %	25.8 %	24.6 %	18.7 %	47.3 %	43.6 %	19.5 %
			pH	6.1	6.0	6.1	6.3	6.4	6.2	8.6	8.5	7.5
	5	1	moisture	14.6 %	22.6 %	18.7 %	21.5 %	41.3 %	17.6 %	31.0 %	55.0 %	18.9 %
			pH	5.7	5.9	5.9	6.1	6.3	6.1	8.7	5.7	7.8
		2	moisture	13.7 %	20.1 %	18.8 %	25.9 %	36.2 %	19.9 %	28.0 %	55.6 %	18.3 %
			pH	5.7	6.0	5.7	6.2	6.1	6.3	8.7	5.6	7.8
	6	1	moisture	13.8 %	21.7 %	13.5 %	23.2 %	49.4 %	17.1 %	29.0 %	54.9 %	18.2 %
			pH	5.9	6.2	5.9	6.2	6.8	6.2	8.9	7.6	7.6
		2	moisture	16.5 %	20.5 %	14.6 %	19.4 %	32.6 %	18.1 %	30.6 %	50.1 %	21.3 %
			pH	6.2	6.3	6.0	6.3	6.7	6.3	8.9	5.7	7.5
	7	1	moisture	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	32.7 %	63.0 %	24.4 %
			pH	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	8.9	5.5	7.9
		2	moisture	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	32.0 %	59.2 %	20.7 %
			pH	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	8.8	5.5	6.8
	8	1	moisture	14.6 %	14.3 %	14.4 %	17.2 %	30.0 %	17.3 %	28.1 %	41.7 %	23.5 %
			pH	5.9	6.0	5.9	6.2	6.5	6.1	8.8	8.7	7.7
		2	moisture	19.0 %	23.3 %	14.7 %	27.5 %	41.2 %	16.0 %	35.1 %	47.7 %	23.1 %
			pH	6.1	6.2	5.8	6.5	6.0	6.2	8.8	5.7	7.0
	9	1	moisture	13.4 %	19.0 %	12.6 %	20.7 %	31.1 %	18.0 %	29.0 %	25.9 %	25.7 %
			pH	6.0	6.0	5.9	6.1	6.6	6.1	9.0	8.9	8.9
		2	moisture	15.1 %	19.2 %	13.9 %	37.7 %	41.5 %	28.2 %	27.0 %	27.4 %	22.4 %
			pH	6.1	6.1	5.7	6.2	6.9	6.1	8.7	8.9	8.1
	10	1	moisture	18.5 %	19.6 %	17.7 %	20.8 %	28.4 %	21.7 %	29.8 %	26.5 %	17.9 %
			pH	5.9	5.9	5.9	6.7	6.0	6.0	8.8	8.8	7.5
		2	moisture	16.8 %	20.7 %	14.7 %	23.3 %	20.7 %	17.1 %	27.7 %	29.6 %	16.5 %
			pH	5.8	5.9	5.7	6.3	6.1	6.0	8.7	8.7	7.5

average pH 6,9 on farm 1 and around pH 5,4 on farm 2. Toward the end of fattening, the litter pH had risen. Average pH on farm 1 was 7,0 during measuring 3. On farm 2 it was 8,0 on average on measuring 2. Bigger values around pH 9 occurred on both farms during last measuring of a fattening period. According to Blake and Hess (2001), NH_3 production remains low below pH 7 and can significantly increase at pH values above 8. The key enzyme "urease" in the NH_3 formation process has its optimum activity at pH 9 (Groot Koerkamp, 1994). Thus, the formation of NH_3 later in the fattening period could be related to urease activity, and a combination of effects with increasing litter moisture is conceivable. Differences in the pH measurements under the feeder line, drinker line, and in the open litter area were also observed, as shown in Table 2.

Conclusions and applications

1. Poor air quality occurred under practical conditions on both farms, with legal upper limits for NH_3 and CO_2 frequently exceeded. These deviations would have remained unnoticed without continuous sensor-based monitoring.
2. Changes in individual barn climate parameters led to increased risks for developing certain welfare issues. Elevated NH_3 levels and threshold exceedances were associated with increased risks of HB and FPD, highlighting the importance of managing litter conditions and ventilation to reduce NH_3 exposure. Variations in CO_2 concentrations within a fattening period were significantly related to changes in risks of FPD, plumage soiling, and body weight changes, demonstrating that CO_2 contributes to broad welfare outcomes.

3. NH_3 and CO_2 followed distinct temporal patterns: CO_2 concentrations peaked early in the fattening period, whereas NH_3 increased toward slaughter age. The lack of temporal correlation confirms that both gases must be monitored independently.
4. Incorporating gas concentrations into ventilation control did not reduce pollutant gas levels in this study, indicating that minor adjustments are insufficient and that more robust, barn-specific ventilation strategies are needed.
5. Continuous, sensor-guided climate monitoring provides a valuable basis for improving air quality and animal welfare in commercial broiler production and should be adopted more widely.
6. Further research is required to determine whether targeted increases in ventilation rates, triggered by elevated NH_3 concentrations, represent an effective and practical mitigation strategy under commercial conditions.
7. Litter moisture and pH varied across both farms. High moisture levels occurred primarily under the drinker line. High pH values occurred toward the end of the fattening period and can be linked to NH_3 production. Although presented only descriptively here, a negative effect on broiler welfare is likely. This effect should be investigated further, and barn management should be optimized.

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CRediT authorship contribution statement

Jan Heck: Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation. **Elke Rauch:** Writing – review & editing, Methodology, Conceptualization. **André Piller:** Writing – review & editing, Validation, Project administration, Methodology, Investigation. **Birgit Schiller:** Investigation. **Michael Erhard:** Resources, Project administration. **Paul Schmidt:** Writing – original draft, Visualization, Formal analysis, Data curation. **Helen Louton:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Disclosures

The authors wish to confirm that there are no known conflicts of interest associated with this publication. The authors declare that the research was conducted in the absence any commercial or financial relationships that could be constructed as a potential conflict of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.japr.2026.100694.

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