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# 1      **Seasonal characteristics of ammonia emission in mechanically ventilated** 2 **sow housing in South Korea**

## 3 4      **Abstract**

5      This study evaluated ammonia (NH<sub>3</sub>) emissions from a mechanically ventilated sow house over 368 days  
6 (January 18, 2021–January 20, 2022). NH<sub>3</sub> concentration (measured using an INNOVA photoacoustic system),  
7 ventilation rate, temperature, and humidity were continuously monitored in three identically structured rooms  
8 according to the European VERA protocol. Seasonal NH<sub>3</sub> concentrations averaged 8.8 ± 3.2 ppm in spring, 5.4  
9 ± 1.0 ppm in summer, 12.2 ± 5.1 ppm in autumn, and 22.4 ± 4.2 ppm in winter. The seasonal ventilation rates  
10 were highest in summer (13,316.4 ± 1,828.6 m<sup>3</sup>/h) and lowest in winter (6,937.9 ± 1,269.6 m<sup>3</sup>/h). The  
11 corresponding seasonal NH<sub>3</sub> emission factors were 7.9 ± 2.2 g/d/pig in spring, 7.4 ± 1.4 g/d/pig in summer, 11.0  
12 ± 3.0 g/d/pig in autumn, and 16.9 ± 4.6 g/d/pig in winter. The annual average emission factor was 10.6 g/d/pig.  
13 NH<sub>3</sub> concentrations were typically highest in the morning and gradually declined throughout the day as  
14 ventilation increased. Correlation analysis revealed a strong positive relationship between NH<sub>3</sub> emissions and  
15 indoor NH<sub>3</sub> concentrations ( $r = 0.93$ ), and a moderate negative relationship with ventilation rate ( $r = -0.57$ ).  
16 Compared to Korea's current official emission factor, the measured emission factor was more than 60% higher,  
17 indicating that the current official value likely underestimates emissions. This discrepancy emphasizes the  
18 urgent need for revised emission factors and standardized measurement protocols. These findings can support  
19 the development of site-specific emission inventories and guide national strategies, including performance-  
20 based environmental regulations and targeted mitigation policies in the livestock sector.

21  
22  
23 **Keywords:** Ammonia emission factor, Gestating sow, Mechanical ventilation, Pig house  
24  
25

## Introduction

According to the United Nations (UN), the global population is projected to grow for the next 60 years [1]. With global population growth, demand for livestock is also increasing [2,3], driving a rise in livestock numbers [4]. As of 2018, approximately 540 million pigs were raised in Asia, representing the highest pig population in the world, with China accounting for a dominant share of around 430 million pigs [4]. South Korea, with about 11.3 million pigs, holds approximately 1.2% of the global share. Global livestock manure production reached 125 megatons of nitrogen (Mt-N), a 23% increase since the 1990s [2]. In particular, livestock manure deposited in agricultural soils contributed 40 Mt-N in Asia in 2018, the largest portion globally and a 50% increase since 1990. Of the 125 Mt-N in global livestock manure, 27 Mt-N was applied to agricultural soils, of which 23 Mt of ammonia (Mt-NH<sub>3</sub>) would have volatilized into the atmosphere in the form of NH<sub>3</sub>. In South Korea, NH<sub>3</sub> emissions from manure in the agricultural sector amounted to 0.183 Mt-NH<sub>3</sub>, accounting for 0.8% of the global total [5,6]. This form of NH<sub>3</sub> pollution contributes to air and soil acidification as well as water eutrophication [7]. Consequently, public concern has grown over the environmental issues arising from increased livestock manure levels [8,9]. Manure emits greenhouse gases, including NH<sub>3</sub> and methane (CH<sub>4</sub>), both directly and during treatment [10,11]. NH<sub>3</sub>, as an alkaline gas that floats in the atmosphere, has multiple environmental impacts [12,13]. High air concentrations of NH<sub>3</sub> can reduce livestock productivity and cause respiratory issues [14]. It also reacts with acidic gases in the atmosphere (e.g., sulfuric or nitric acid) to form secondary particulate matter [15-17], which adversely affects ecosystems [18,19]. NH<sub>3</sub> is classified as an indirect greenhouse gas due to its potential for producing greenhouse gases [20,21]. NH<sub>3</sub> converts to nitrate (NO<sub>3</sub><sup>-</sup>) in soil, which then transforms into nitrous oxide (N<sub>2</sub>O) through denitrification [22,23]. Nitrous oxide has a greenhouse effect approximately 300 times stronger than carbon dioxide. Therefore, it is urgent to manage NH<sub>3</sub> emission due to its extensive negative effects on the environment and long-term bolstering of climate change [24].

Given these concerns, recent studies have reassessed the accuracy of Korea's emission inventory and the suitability of existing emission factors. Lee et al. (2024) [25] reported that NH<sub>3</sub> emissions from Korea's manure management sector may be ~33% higher than official estimates, indicating the need to revise current factors. Choi et al. [26] conducted long-term measurements at a modern commercial pig farm and suggested that existing Korean emission factors may be overestimated, with clear seasonal variation and key drivers such as ventilation rate and growth stage. Kang et al. (2025) [27] developed an NH<sub>3</sub> emission factor for open laying-hen houses in Korea using a tracer gas method in accordance with the VERA protocol, showing that operational conditions (e.g., curtain position) can strongly influence NH<sub>3</sub> concentrations and emissions. For swine housing, the NH<sub>3</sub> emission factors used in South Korea (classified by rearing stage in the national emission inventory) are 5.2 g/d/pig for nursery pigs, 12.3 g/d/pig for growing pigs, 14.2 g/d/pig for finishing pigs, and 30.1 g/d/pig for sows. These factors were developed in 2007 by the National Institute of Environmental Research [28,29] and have not been updated to reflect current farm conditions. In addition, earlier Korean measurements often covered only short periods (1 d to 1 week), lacked a standardized protocol, and did not consistently capture Korea's strong seasonal variability or differences between naturally and mechanically ventilated systems. Since the Ministry of Environment's Second Comprehensive Odor Control Policy (2019) required pig facilities to be enclosed, the share of mechanically ventilated houses has increased, making emission estimates based on

64 outdated assumptions more uncertain. Moreover, NH<sub>3</sub> emissions vary with ventilation-controlled temperature  
65 and humidity, highlighting the need for long-term datasets to quantify these relationships.

66 This study conducted continuous NH<sub>3</sub> measurements for 368 days in a mechanically ventilated sow house.  
67 NH<sub>3</sub> concentration, ventilation rate, temperature, and relative humidity were measured simultaneously in three  
68 separate rooms within the same facility to capture spatial differences. NH<sub>3</sub> emissions were calculated using the  
69 European Verification of Environmental Technologies for Agricultural Production (VERA) protocol, which is  
70 widely applied in the Netherlands, Germany, and Denmark. The resulting emission factors are based on long-  
71 term, multi-room measurements under actual operating conditions and provide a stronger basis than previous  
72 short-term Korean studies. The accurate NH<sub>3</sub> emission estimates provided in this study support the formulation  
73 of policies and regulatory frameworks for managing pollution. This can contribute to achieving carbon  
74 neutrality and environmental safety targets by controlling NH<sub>3</sub> emissions. These issues underscore the necessity  
75 of revising national emission factors to reflect actual farm-level conditions. Moreover, updated factors can  
76 inform the Ministry of Environment and relevant authorities in designing emission-based regulation systems,  
77 establishing benchmark values for air pollution control in enclosed livestock facilities. Further research linking  
78 structural characteristics of livestock housing—such as air inlet orientation, manure storage layout, and  
79 ventilation system design—with ammonia emissions would help guide housing-specific mitigation strategies  
80 and improve inventory accuracy.

81

82

## Materials and Methods

### 83 Sow house structure and environment

84 This study estimated NH<sub>3</sub> emission factors for sow (gestation) houses in rural Danyang, Chung-Buk, South  
85 Korea, as a follow-up to previous research [30-31]. Measurements were conducted over 368 d, from January 18,  
86 2021, to January 20, 2022. Fig. 1 presents a cross-sectional view of the experimental sow houses. The emission  
87 experiment treated typical enclosed sow houses in Korea as a mega chamber, where each pig room is considered  
88 an individual chamber. Ventilation in the sow houses draws clean outside air into the mid-ceiling area, which  
89 serves as a supply-air plenum, and delivers it into the pig rooms through an air-permeable (perforated) ceiling.  
90 Air from the pig rooms is exhausted by four ceiling-mounted fans and discharged directly outdoors. (Fig 1). The  
91 sow house floors consist of concrete and plastic slats (1:1 ratio), allowing manure and urine to fall into a pit as  
92 part of a storage system. The manure stored in the pit was discharged weekly in consistent amounts, maintaining  
93 approximately 70–80% of the total volume.

94 To enhance the reliability and accuracy of the measurements, three identically structured rooms were selected  
95 and monitored simultaneously. Each room included five rearing sections and six pens. Rooms 1, 2, and 3 housed  
96 154, 154, and 156 sows, respectively, of three-way crossbreeds (Yorkshire, Landrace, and Duroc, respectively).  
97 Pregnant sows near delivery were transferred to a farrowing section (approximately 26 sows) for farrowing and  
98 nursing, lasting 4–5 weeks. Afterward, they were returned and monitored under environmental conditions  
99 recommended by the VERA test protocol (Table 1) [32]. The density in the sow houses was 2.2 m<sup>2</sup>/sow,  
100 meeting South Korea's legal requirement of 1.4 m<sup>2</sup>/sow and the EU's guideline of 2.25 m<sup>2</sup>. Table 1 outlines the  
101 main components of the feed supplied during the measurement period, with the following key nutrient contents:  
102 crude protein  $\leq$ 13.5%, crude fat  $\geq$ 3%, calcium  $\geq$ 0.65%, and phosphorus  $\leq$ 1.5%. This feed composition met the

103 Korean crude protein allowance of  $\leq 16\%$  (revised to 15% for sows and 13% for pregnant sows after July 2022).  
104 After the revision, the crude protein content was 2–3% higher than that in feed in Denmark and Finland.  
105 Although the VERA protocol was originally developed for European housing systems, its application in this  
106 study is justified by the structural and operational similarities shared with modern Korean sow houses. The  
107 target facilities were enclosed and mechanically ventilated, aligning with VERA's core design criteria. In  
108 particular, the sow density (2.2 m<sup>2</sup>/sow), group size ( $\geq 154$  pigs), and extended monitoring period (368 days) not  
109 only meet but exceed the VERA protocol's minimum requirements. This supports the methodological validity of  
110 using the VERA framework under South Korean field conditions.

111

### 112 **Sow house monitoring**

113 NH<sub>3</sub> concentration was monitored in real-time using a photoacoustic spectroscopy analyzer (INNOVA 1512i,  
114 LumaSense Technologies, Ballerup, Denmark). Photoacoustic spectroscopy determines substance  
115 concentrations by measuring the acoustic signals generated by irradiating the sample with light at specific  
116 wavelengths. A multi-sampler (INNOVA 1409, 24 port; LumaSense Technologies) was connected to the  
117 analyzer to measure concentrations in rooms 1–3 and at the air inlet. VERA guidelines recommend  
118 measurements should be taken at least once per hour. However, considering instrument load and field conditions,  
119 measurements were taken every 2 h. For each measurement, we calculated the average concentration from 4–6  
120 readings out of six measurements as the representative value. The analyzer operates by drawing in gas for each  
121 measurement and analyzing it within a closed chamber. This was done considering the minimum number of  
122 intakes required for the target gas concentration to reach the desired level [33]. Prior to monitoring, the analyzer  
123 was calibrated using high-purity nitrogen gas (99.999%, Daedeok Gas, Incheon, South Korea) and NH<sub>3</sub> standard  
124 gas (Rigas, Daejeon, Korea). Measurements were taken at seven standard gas concentrations (0, 5, 10, 20, 25, 30,  
125 and 50 ppm) using mass flow controllers (VIC-D220, NH<sub>3</sub> flow rate 1.5 SLPM (Standard Liters Per Minute),  
126 MFC (Mass Flow Controller) Korea, Incheon, South Korea) for dilution. Each concentration of standard gas  
127 was measured 10–15 times, and the mean of the last five measurements was used as the representative  
128 concentration. The deviation between the reference concentration and measured values was approximately 2%  
129 (Fig. S1(b)). The calibration curve, based on representative values for each concentration, was  $y = 0.9985x +$   
130  $0.0579$  ( $R^2 = 0.9999$ , Fig. S1(a)). We measured the ventilation rate using a small device, designed according to  
131 the standards of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, attached to the  
132 exhaust fan [BV Multifan 4E50 (Ø630), Vostermans, Venlo, Netherlands]. The ventilation fans in the sow  
133 houses were not operated below 30% capacity. We measured the airflow rate (m<sup>3</sup>/h) at operating levels of 30%,  
134 50%, 70%, and 100% to calculate the ventilation rate [33]. The operating rate of the ventilation fans in the sow  
135 houses was measured in 1% increments. To estimate ventilation rates for missing intervals (31–49%, 51–69%,  
136 and 71–99%), we applied the logistic curve proposed by Jo et al. [34].

137

### 138 **Estimation of ammonia emission factor in sow house**

139 NH<sub>3</sub> emissions were calculated following the method outlined in the VERA test protocol [30], as illustrated in  
140 Equations 1 and 2.

$$E_{NH_3} \text{ (g/h/pig)} = (Ammonia_{out} - Ammonia_{in}) \times \frac{17.03}{24.45} \times Ventilation \times pig^{-1} \times 10^{-3} \quad (1)$$

$$EF_{NH_3} \text{ (g/d/pig)} = \frac{1}{d} \sum (E_{NH_3} \text{ (start date)} + \dots + E_{NH_3} \text{ (end date)}) \quad (2)$$

141  $E_{NH_3}$ : amount of  $NH_3$  emitted by a single pig per hour (**g/h/pig**)

142  $Ammonia_{out}$ :  $NH_3$  concentration at the exhaust vent (ppm)

143  $Ammonia_{in}$ :  $NH_3$  concentration at the inlet vent (ppm)

144  $Ventilation$ : average ventilation rate ( $m^3/h$ ).

145  $pig$ : total count of pigs raised in the sow houses

146

147 The  $NH_3$  concentration in the pen was calculated by subtracting the inlet concentration ( $Ammonia_{in}$ , ppm)

148 from the exhaust concentration ( $Ammonia_{out}$ , ppm). The data were converted to  $mg/m^3$  to estimate the hourly

149  $NH_3$  emission, which were summed to determine daily emissions. Outliers were excluded following the VERA

150 test protocol, which defines outliers as values exceeding the upper quartile (75th; 3Q) + [ $3 \times$  interquartile range

151 (IQR)] or below the lower quartile (25th; 1Q) – ( $3 \times$  IQR). Finally, we calculated the  $NH_3$  emission factor per

152 pig over the measurement period in the sow houses based on the summed daily emissions (g/d/pig). Pearson

153 correlation analysis was conducted to examine relationships among variables using R (R Foundation for

154 Statistical Computing, Vienna, Austria) in RStudio (Posit Software, Boston, MA, USA). In addition, multiple

155 regression analysis and one-way analysis of variance (one-way ANOVA) were performed using IBM SPSS

156 Statistics (IBM Corp., Armonk, NY, USA) to assess the combined effects of explanatory variables and to

157 evaluate differences among groups, respectively, with statistical significance set at  $p < 0.05$ . Regression outputs

158 were summarized as unstandardized coefficients (B), standardized coefficients ( $\beta$ ), standard errors, p-values,

159 and 95% confidence intervals (Table S2). Regression assumptions were evaluated using residual diagnostics

160 based on predicted values and standardized residuals.

161

## 162 Results

### 163 Results for different environmental variables

164 Fig. 2 illustrates the  $NH_3$  concentrations, ventilation rates, internal temperatures, and relative humidity in each

165 room over the 368-d measurement period (January 18, 2021–January 20, 2022). Spring was defined as March to

166 May, summer as June to August, autumn as September to November, and winter as December to February.

167 South Korea's climate features hot humid summers and cold dry winters. Table 2 summarizes the mean and

168 standard deviation of  $NH_3$  concentration, ventilation rate, internal temperature, and relative humidity in rooms

169 1–3 across the four seasons. The highest  $NH_3$  concentration was observed in room 3 during winter (34.1 ppm),

170 while the lowest was in room 2 during summer (3.7 ppm). The highest ventilation rate occurred in room 3

171 during summer (17,030.4  $m^3/h$ ), and the lowest in room 1 during autumn (3,805.4  $m^3/h$ ) (Table S1). Room 1

172 exhibited consistently lower  $NH_3$  concentrations and emissions, likely due to enhanced dilution from outside-air

173 infiltration near the entrance. The average internal temperatures in rooms 1–3 for spring, summer, autumn, and

174 winter were 20.9 °C, 25.7 °C, 22.4 °C, and 19.6 °C, while the average relative humidity was 44.3%, 87.9%,

175 63.8%, and 40.1%, respectively. The temperature ranges in the sow houses during summer and winter were

176 22.3–29.5 °C and 18.0–21.4 °C, while the relative humidity levels were 60–100% and 16–53%, respectively,  
177 reflecting high seasonal variation in environmental conditions. Seasonal average NH<sub>3</sub> concentrations in rooms  
178 1–3 was 8.8 ppm (spring), 5.4 ppm (summer), 12.2 ppm (autumn), and 22.4 ppm (winter). Seasonal ventilation  
179 rates averaged 9244.7 m<sup>3</sup>/h (spring), 13 316.4 m<sup>3</sup>/h (summer), 9225.0 m<sup>3</sup>/h (autumn), and 6937.9 m<sup>3</sup>/h (winter).  
180 Given the pronounced seasonal and day-to-day variability in NH<sub>3</sub> concentration observed across rooms over the  
181 368-d measurement period (Fig. 2, Table 2), we quantified uncertainty in the room-level overall mean NH<sub>3</sub>  
182 concentration to provide a statistically supported range around these period-average estimates. Moving-block  
183 bootstrap resampling was repeated B = 5000 times using blocks of L = 24 h (i.e., 24 consecutive hourly  
184 observations) to preserve temporal autocorrelation, and 95% confidence intervals (CIs) were defined as the  
185 2.5th–97.5th percentiles of the resulting bootstrap distributions [35]. Over the full measurement period, the  
186 overall mean NH<sub>3</sub> concentration was 11.06 ppm (95% CI: 10.54–11.58) in Room 1, 12.30 ppm (11.74–12.89) in  
187 Room 2, and 12.18 ppm (11.61–12.77) in Room 3. These CIs corresponded to an uncertainty range of  
188 approximately –4.6% to +4.9% relative to the room means. The non-overlapping 95% CIs between Room 1 and  
189 Rooms 2 and 3 are consistent with higher overall mean NH<sub>3</sub> concentrations in Rooms 2 and 3 than in Room 1.

190 NH<sub>3</sub> concentration during winter was more than four times higher than that in summer. While NH<sub>3</sub> volatilizes  
191 more easily at higher temperatures, leading to higher concentrations, an opposite trend was observed in this  
192 study. This may reflect the differences in experimental factors such as sow house structure, ventilation type,  
193 feed composition, and seasonal characteristics [36–38]. Fig. 3a shows the seasonal NH<sub>3</sub> concentrations,  
194 averaged across rooms 1–3. During summer, the NH<sub>3</sub> concentration was 3.9–9.6 ppm and the internal  
195 temperature was 23.0–28.3 °C. In winter, the NH<sub>3</sub> concentration was 13.4–31.0 ppm and the internal  
196 temperature was 18.1–21.0 °C. Therefore, NH<sub>3</sub> concentration was low at high internal temperatures in summer,  
197 whereas it was high at lower internal temperatures in winter. This difference from typical research findings may  
198 be explained by two factors.

199 First, the potential difference in ventilation rate according to seasonal temperature changes (Fig. 3b). The  
200 operation rate of ventilation fans in sow houses is adjusted based on internal temperature. In this study, the  
201 ventilation rate in summer was approximately twice that in the winter. In winter, ventilation rates are decreased  
202 to minimize dramatic temperature fluctuations to help the pigs with body temperature regulation. In contrast,  
203 ventilation rates are increased in summer to help lower the pigs' body temperature. NH<sub>3</sub> accumulates when  
204 ventilation rates decrease, whereas increased ventilation rates promote the mixing of NH<sub>3</sub> with outside air,  
205 promoting outward emission and decreasing internal NH<sub>3</sub> concentrations [31,39].

206 The second factor is the individual differences in drinking and feeding behaviors. Drinking behavior in pigs is  
207 closely linked to feed intake and body temperature regulation (pigs increase their water intake on hot compared  
208 with cold days) [40]. Within the ideal temperature range (25–30 °C), pigs may consume 9–12 L of water per day.  
209 At higher temperatures (>30 °C), water intake doubles to approximately 15 L/d for pigs weighing >65 kg [41].  
210 The high relative humidity under high temperatures (Fig. 3b) may indirectly reflect the increased water intake  
211 during hot days, when feed intake normally decreases. Seasonal variations in drinking behavior and ventilation  
212 collectively influence in-house NH<sub>3</sub> levels. Under hot conditions, pigs increase water intake, and high relative  
213 humidity can further exacerbate heat stress and alter water-use patterns [42], while higher summer ventilation  
214 enhances dilution and reduces indoor NH<sub>3</sub> concentrations. At 10 °C, pigs consume 3.9 kg of feed per day, but

215 this drops to 2.6 kg/d at 25 °C, an approximately 1.5-fold reduction, in 100-kg pigs [43]. Increased water intake  
216 and higher temperatures reduce appetite, leading to lower feed intake. Therefore, during summer, reduced feed  
217 intake decreases manure production. Higher water loss due to increased water intake may further reduce NH<sub>3</sub>  
218 concentration in manure during summer compared with that in winter [44-45]. Moreover, seasonal variations in  
219 water intake and ventilation rates collectively influence in-house ammonia levels. In summer, increased water  
220 intake and ventilation reduce ammonia concentrations. In contrast, reduced ventilation and water intake in  
221 winter elevate fecal output and ammonia levels. Indoor NH<sub>3</sub> concentrations can be influenced by manure  
222 management (removal timing and frequency), sow activity levels, and humidity–temperature conditions that  
223 affect volatilization and indoor accumulation (Philippe et al.). Seasonal concentration patterns have been  
224 reported to vary with housing operation and temperature-control settings [23,46]. In this study, manure-surface  
225 processes such as nitrogen speciation (NH<sub>4</sub><sup>+</sup>/TAN) and near-surface airflow were not directly evaluated. Future  
226 work incorporating these factors is needed to better elucidate NH<sub>3</sub> volatilization mechanisms in mechanically  
227 ventilated pig houses. These findings underscore the need for ammonia mitigation strategies and effective slurry  
228 management in pig houses [47,48].

229

### 230 **NH<sub>3</sub> emission factors in sow houses**

231 Seasonal NH<sub>3</sub> emission factors (Fig. 4) were calculated using concentration and ventilation data for each  
232 room (Table 3). The seasonal averages were 7.9 g/d/pig (spring), 7.4 g/d/pig (summer), 11.0 g/d/pig (autumn),  
233 and 16.9 g/d/pig (winter). The overall average NH<sub>3</sub> emission factor was 10.6 g/d/pig, which is over 60% lower  
234 than the current domestic emission factor of 30.1 g/d/pig. There are four main reasons for the difference  
235 between our and previous findings, the first being technological differences. Previous studies used the  
236 indophenol method (ES 01303.1d) as specified in the Korean Standard Testing Method for Atmospheric  
237 Pollution Process for NH<sub>3</sub> measurement. However, modern computing advancements allow for more precise  
238 real-time measurement. Unlike previous studies, which measured NH<sub>3</sub> over short periods of up to 7 d, this study  
239 monitored emissions continuously for 368 d using real-time monitoring equipment. Second, previous studies  
240 used the EPA methodology, which may underestimate/overestimate concentrations depending on chamber  
241 placement. In this study, we followed the VERA protocol, treating the enclosed sow houses as a single mega  
242 chamber for emissions measurement. Third, prior research did not consider the differences between open and  
243 enclosed sow house when calculating emission factors. However, the legal mandate moving farmers toward  
244 enclosed sow houses requires a reevaluation of the contributions of enclosed mechanically ventilated sow house  
245 designed to standard specifications. Fourth, the number of pigs per room varied widely from 8 to 105 in  
246 previous studies. In contrast, we study maintained a consistent number of pigs between rooms.

247

### 248 **Variation in diurnal trends and correlation analysis**

249 Fig. 5 illustrates the variation in the diurnal trends of NH<sub>3</sub> concentration, indoor temperature, ventilation rate,  
250 and NH<sub>3</sub> emissions in rooms 1–3 during the measurement period. Each variable exhibited distinct trends. Fig. 6  
251 presents the correlation analysis results for data averaged across rooms. Internal NH<sub>3</sub> concentrations decreased  
252 as ventilation rates increased, due to mixing with incoming air and expulsion. Ventilation rates increased after  
253 sunrise with rising temperatures, peaking around 12–1 PM, and decreased after sunset, reaching a minimum

254 around 12–1 AM In contrast, NH<sub>3</sub> concentration increased in the morning to but decreased sharply as ventilation  
255 rates rose. NH<sub>3</sub> concentrations in rooms 1–3 peaked around 6–7 AM (14.2 ppm, 15.1 ppm, and 14.9 ppm,  
256 respectively) and were lowest around 4–5 PM (9.8 ppm, 11.1 ppm, and 11.0 ppm, respectively). While the  
257 overall trends were similar between rooms, NH<sub>3</sub> emissions in room 1 were relatively lower. This difference is  
258 likely due to the proximity of room 1 to the entrance, where outside air may have been introduced during worker  
259 entry, resulting in lower NH<sub>3</sub> concentration and emissions. Correlation analysis revealed a strong negative  
260 correlation between ventilation rate and NH<sub>3</sub> concentration ( $r = -0.80$ ). Ventilation rates, adjusted according to  
261 internal and external temperatures, showed a strong correlation with temperature. Internal temperatures in rooms  
262 1–3 peaked around 2–3 PM (23.1 °C, 23.0 °C, and 23.9 °C, respectively) and were lowest 12–1 AM (21.2 °C,  
263 21.3 °C, and 21.7 °C, respectively). Throughout the seasons, internal temperatures remained at 21.2–23.9 °C.  
264 We observed a strong positive correlation ( $r = 0.92$ ) between ventilation rate and internal temperature. The NH<sub>3</sub>  
265 emission factor did not show significant variation by time of day ( $\pm 0.1$ ). NH<sub>3</sub> emission factors were influenced  
266 by internal NH<sub>3</sub> concentrations and ventilation rates, with seasonal variations affecting their relationship (Fig.  
267 S3). The emission factor was negatively correlated with internal temperature ( $r = -0.51$ ) and humidity ( $r = -$   
268  $0.42$ ). Correlation analysis showed that ventilation rate was strongly associated with diurnal NH<sub>3</sub> concentration  
269 and was also strongly correlated with indoor temperature, indicating covariance among predictors. We therefore  
270 fitted room-specific multiple linear regression models to estimate the independent associations of ventilation  
271 rate, indoor temperature, and relative humidity with NH<sub>3</sub> concentration (Table S2). Ventilation rate was a  
272 significant negative predictor in all rooms ( $B < 0$ ,  $p < 0.001$ ), indicating lower NH<sub>3</sub> concentrations at higher  
273 ventilation rates. Temperature and relative humidity exhibited room-dependent associations, with significant  
274 effects in Rooms 2 and 3 but not in Room 1 ( $p > 0.05$ ). Diurnal NH<sub>3</sub> concentration was primarily associated  
275 with ventilation dynamics, and multiple regression identified ventilation as the only predictor consistently  
276 associated with lower NH<sub>3</sub> across rooms, whereas temperature and relative humidity showed room-dependent  
277 associations. To evaluate the representativeness of treating each enclosed room as an independent chamber,  
278 inter-room differences in key variables were assessed using one-way ANOVA (Table S3). NH<sub>3</sub> concentration  
279 showed no statistically significant inter-room difference ( $p = 0.061$ ), and relative humidity was also comparable  
280 among rooms ( $p = 0.306$ ). Ventilation rate ( $p < 0.001$ ) and indoor temperature ( $p = 0.003$ ) showed significant  
281 inter-room differences, which likely reflect room-specific airflow patterns associated with structural and  
282 operational variability within the facility. Taken together, the absence of a statistically significant inter-room  
283 difference in NH<sub>3</sub> concentration supports the chamber-based approach as a reasonable representation of room-  
284 level NH<sub>3</sub> concentration patterns under the studied conditions.

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### 288 **Comparison of emission factors by country**

289 This study provides a foundational resource for estimating domestic NH<sub>3</sub> emission factors and supports the  
290 development and implementation of effective NH<sub>3</sub> mitigation and regulatory policies. NH<sub>3</sub> emissions are  
291 influenced by factors such as stocking density, manure storage methods, climate, and ventilation systems  
292 [10,43]. For this reason, differences in NH<sub>3</sub> emission factors between Korea and Europe are expected due to the  
293 distinct environmental and livestock conditions (Table 4). Additionally, most previous studies use varying units,

294 such as LU (Livestock Unit), AP (Animal Place), and LSU (Livestock Standard Unit), making direct  
295 comparisons of emission factors between countries challenging. To enable a more consistent comparison, the  
296 emission factor derived in Section 3.3 (g/d/pig) was converted to an annual basis (kg/pig/year).

297 The NH<sub>3</sub> emission factor calculated in this study was 3.87 kg/pig/year, and it was compared with those  
298 reported in Wales (3.01 kg/AP/year) [48], the Netherlands (4.2 kg/AP/year) [49], Germany (4.8 kg/AP/year)  
299 [32], and Ireland (3.87–4.93 kg/AP/year) [50]. Direct comparison of these values is limited because the reported  
300 units differ and because detailed information on stocking density, space allowance per sow, and ventilation and  
301 management practices is not consistently available across studies. To improve comparability, emission factors  
302 originally reported on an animal place (AP) basis were normalized to a pig-based unit using stocking density as  
303 a common reference. AP-based emission factors (kg NH<sub>3</sub>·AP<sup>-1</sup>·year<sup>-1</sup>) were converted to pig-based emission  
304 factors (kg NH<sub>3</sub>·pig<sup>-1</sup>·year<sup>-1</sup>) by applying the ratio of legal stocking density to actual stocking density (EF pig =  
305 EF<sub>AP</sub> × SD<sub>legal</sub> / SD<sub>actual</sub>) [32]. For studies in which only legal stocking density was reported, the actual stocking  
306 density was assumed to be identical to that of the present study (2.2 m<sup>2</sup>·pig<sup>-1</sup>) to allow harmonized  
307 normalization. This normalization approach does not account for all sources of variability among countries,  
308 including differences in ventilation control, manure management practices, and occupancy rates. Consequently,  
309 the normalized emission factors presented in Table 4 should be interpreted as indicative values rather than as  
310 strictly quantitative comparisons. Considering these factors, the NH<sub>3</sub> emission factor calculated in this study  
311 falls within a similar range to the values presented in Table 4. Notably, when comparing with the Czech  
312 Republic, which uses the same unit, the difference was less than 10% [47]. This comparison is supported by  
313 similarities in measurement conditions, as the Czech study was conducted in mechanically ventilated pig houses  
314 and quantified NH<sub>3</sub> emissions using photoacoustic monitoring (INNOVA) based on inlet–outlet concentration  
315 differences and ventilation rates, comparable to the approach adopted in the present study. Furthermore, NH<sub>3</sub>  
316 emission factors in Europe are typically derived using standardized methodologies such as the VERA protocol.  
317 As this study also employed the VERA protocol, its results are highly reliable. In conclusion, the NH<sub>3</sub> emission  
318 factor determined in this study generally aligns with values reported in Europe and other countries. This study  
319 provides meaningful data for establishing domestic NH<sub>3</sub> emission factors and is expected to contribute  
320 significantly to the development of effective NH<sub>3</sub> mitigation and regulatory policies in Korea. The data  
321 generated in this study can directly inform emission charge systems, odor control regulations, and mitigation  
322 guidelines that are currently under revision as part of Korea's national air quality and livestock management  
323 strategies.

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## Conclusion

This long-term study evaluated the ammonia emissions and environmental characteristics of three rooms with similar structures in a mechanically ventilated sow house.  $\text{NH}_3$  concentration, ventilation rate, temperature, and humidity were monitored in real time using the mega-chamber method, which treats each enclosed room as a separate chamber. Data collection adhered to the European VERA protocol, with  $\text{NH}_3$  concentrations measured using photoacoustic spectroscopy equipment. Strong seasonal variation was observed in the average  $\text{NH}_3$  concentrations, ventilation rates, and  $\text{NH}_3$  emission factors. Analysis of the diurnal trends revealed that ventilation rates gradually increased with rising temperatures after sunrise and decreased after sunset. Conversely,  $\text{NH}_3$  concentrations gradually increased during the early morning hours and then dropped sharply as ventilation rates increased to compensate for increasing temperatures. We observed significant relationships between  $\text{NH}_3$  emissions and internal concentration or ventilation rate. The emission factors of the studied sow house were similar to those reported in Europe and the USA, but they differed greatly from the current domestic emission factor. These results indicate that revising the current national  $\text{NH}_3$  emission factors is necessary and that more accurate emission factors reflecting actual housing and management conditions in Korean pig farms should be developed. The findings of this study suggest that the long-term monitoring framework applied herein may serve as a practical monitoring protocol for developing  $\text{NH}_3$  emission factors tailored to Korean livestock facilities. This approach may enable the development of facility-type-specific  $\text{NH}_3$  emission factors, rather than reliance on a one-size-fits-all emission factor, by accounting for differences in housing structure, ventilation systems, and management practices across pig production facilities. National emission factor frameworks should be updated to reflect the increasing proportion of enclosed, mechanically ventilated pig houses in Korea. This study provides a useful framework for updating national  $\text{NH}_3$  emission factors and evaluating the effectiveness of  $\text{NH}_3$  control measures aimed at reducing indirect greenhouse gas emissions and achieving carbon neutrality. To further refine emission factor development and mitigation strategies, future research should incorporate continuous, multi-seasonal monitoring and examine the effects of housing design parameters—such as floor structure, air inlet orientation, and manure storage layout—on ammonia emissions. These efforts will enhance the robustness of national inventories and support housing-specific regulatory approaches.

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Table 1. Comparison of experimental sow housing conditions with VERA protocol criteria to validate applicability in the Korean context

Criterion	Gestation Sow						
	VERA			This Study			
Animal occupation rate (%)	90–100			100			
Minimum number of animals in test compartment (pigs)	20			154–156			
Minimum period in test compartment (d)	Up to 120			368			
Crude protein feed requirements (%)	11–14			13.5			
Minimum production requirements (piglets per sow <sup>-1</sup> year <sup>-1</sup> )	22			Up to 22			
	Feed composition (%)						
	Crude protein	Crude fat	Calcium	Phosphorus	Crude fiber	Crude ash	Lysine
	≤13.50	≥3.00	≥0.65	≤1.50	≤8.00	≤8.00	≥0.60

Table 2. Mean and standard deviation of NH<sub>3</sub> concentration, indoor temperature, ventilation rate, and relative humidity in rooms 1–3

		NH <sub>3</sub> concentration (ppm)		Ventilation rate (m <sup>3</sup> /h)		Temperature (°C)		Relative humidity (%)	
		Average	SD	Average	SD	Average	SD	Average	SD
Room 1	Spring	8.3	3.0	8944.70	1642.60	20.6	1.3	45.1	14.1
	Summer	5.2	0.8	12855.30	1715.90	25.4	1.2	88.1	10.2
	Autumn	10.9	4.4	7721.70	2661.20	22.2	1.9	64.7	12.9
	Winter	21.0	3.7	6298.30	1028.30	19.5	0.8	41.7	12.0
Room 2	Spring	9.0	3.1	9360.00	1775.60	20.7	1.2	42.9	14.5
	Summer	5.5	1.0	12859.30	1664.90	25.0	1.4	87.5	10.9
	Autumn	13.1	5.1	9529.20	2056.50	22.3	1.6	62.1	15.3
	Winter	23	4.2	7444.70	1273.00	19.8	1.0	36.8	13.3
Room 3	Spring	9.1	3.3	9429.50	1952.70	21.2	1.5	45	14.2
	Summer	5.4	1.0	14234.60	1746.50	26.7	1.6	88.1	10.2
	Autumn	12.5	5.5	10424.10	3151.00	22.7	2.3	64.7	13.2
	Winter	23.2	4.5	7070.80	1214.00	19.5	0.7	41.7	12.2

Table 3. Seasonal mean and standard deviation of NH<sub>3</sub> emission factors in sow-house rooms 1–3

	Room 1		Room 2		Room 3	
	Average	SD	Average	SD	Average	SD
Spring	7.2	2.1	8.3	2.5	8.2	1.8
Summer	6.9	1.0	7.4	1.5	7.8	1.5
Autumn	8.1	1.3	12.5	2.6	12.6	2.2
Winter	14.0	2.6	18.8	4.8	17.9	4.5

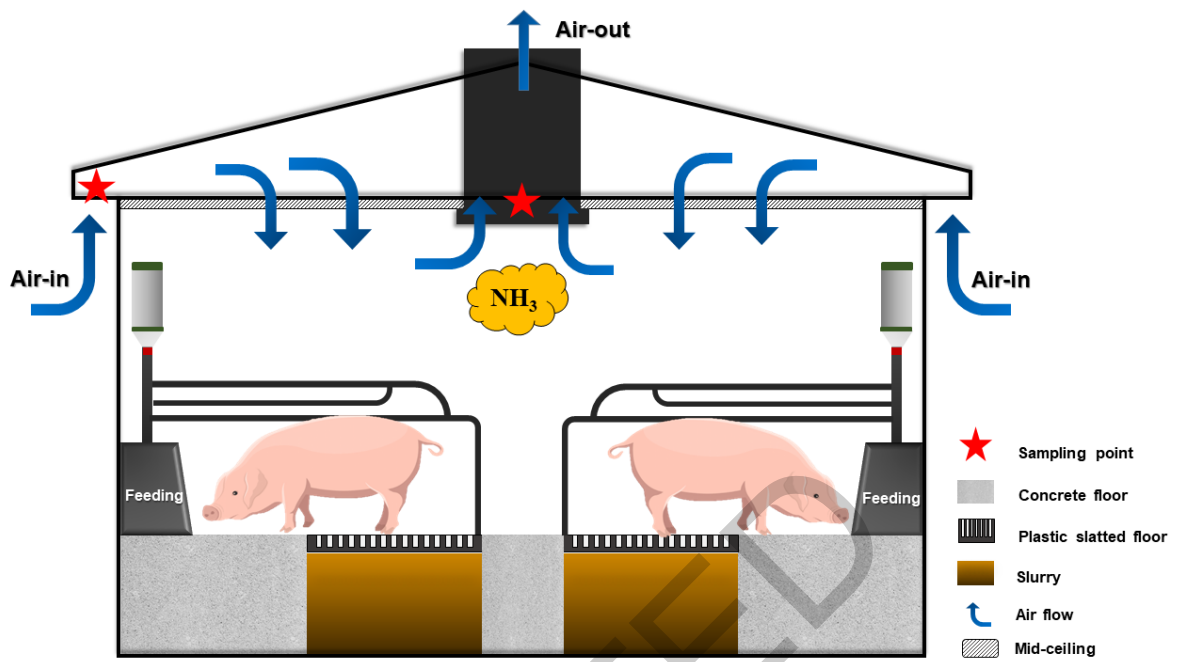
Table 4 Comparison of NH<sub>3</sub> emission factors and animal stocking regulations by country

Country	Type of pig	Stocking density (m <sup>2</sup> /pig)	VERA (kg/AP <sup>a</sup> /year)	NH <sub>3</sub> emissions (kg/pig/year)	Reference
South Korea	Sows	2.2	6.08*	3.87	This study
Netherlands	Sows	2.25	4.2	4.30**	Van der Zee, 2021 [50]
Germany	Sows	2.45	4.8	5.35**	VERA, 2018 [32]
Wales	Sows	2.25	3.01	3.08**	Wales, 2022 [49]
Ireland	Sows	2.25	3.87-4.93	3.96-5.04**	Hayes et al., 2006 [51]
Czech Republic	Sows	2.25	4.2*	4.3	Kunes et al., 2022 [45]

<sup>a</sup>AP, animal place—required area needed to raise one animal

\*  $EF_{pig} = EF_{AP} \times SD_{legal} / SD_{actual}$

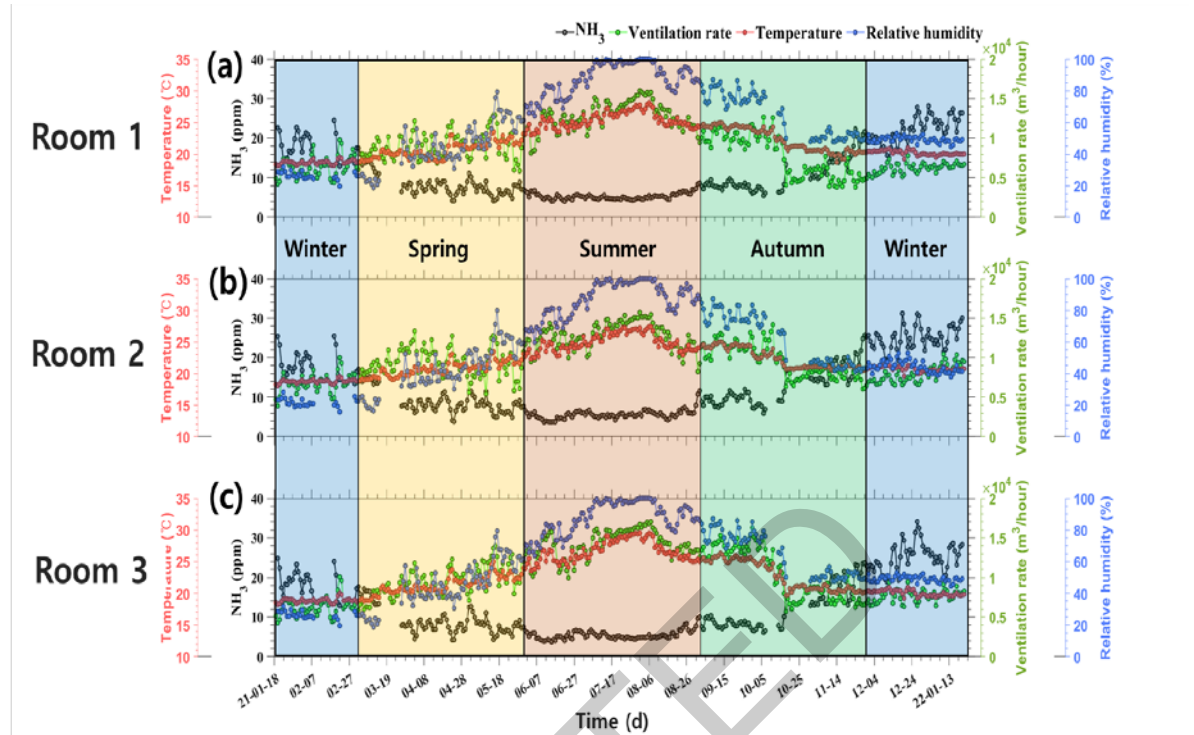
\*\*  $EF_{AP} = EF_{pig} \times SD_{actual} / SD_{legal}$



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Fig. 1. Cross-sectional view of experimental sow houses

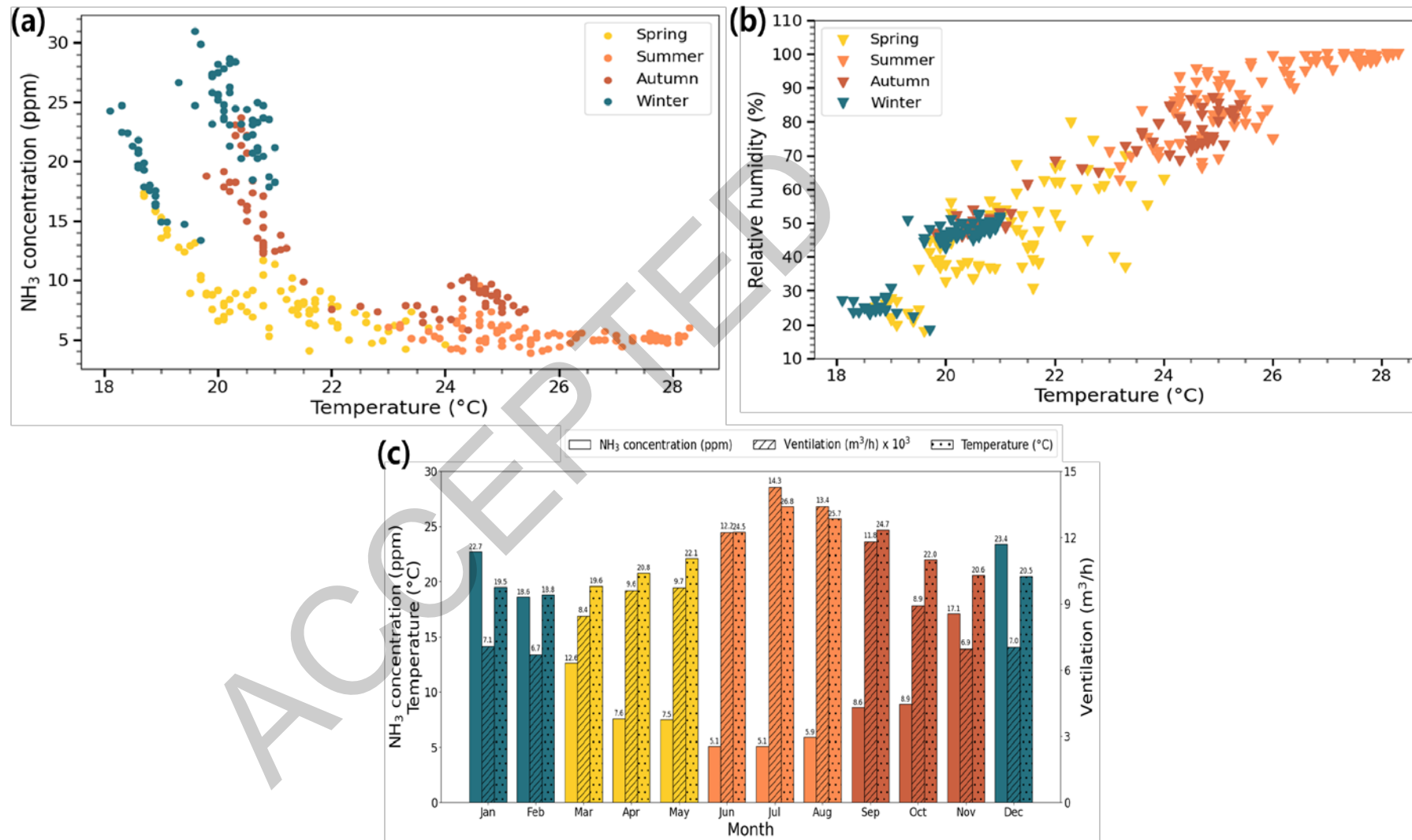
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Fig. 2. Daily monitoring results for  $\text{NH}_3$  concentration, indoor temperature, ventilation rate, and relative humidity in rooms (a) 1, (b) 2, and (c) 3 of the sow houses

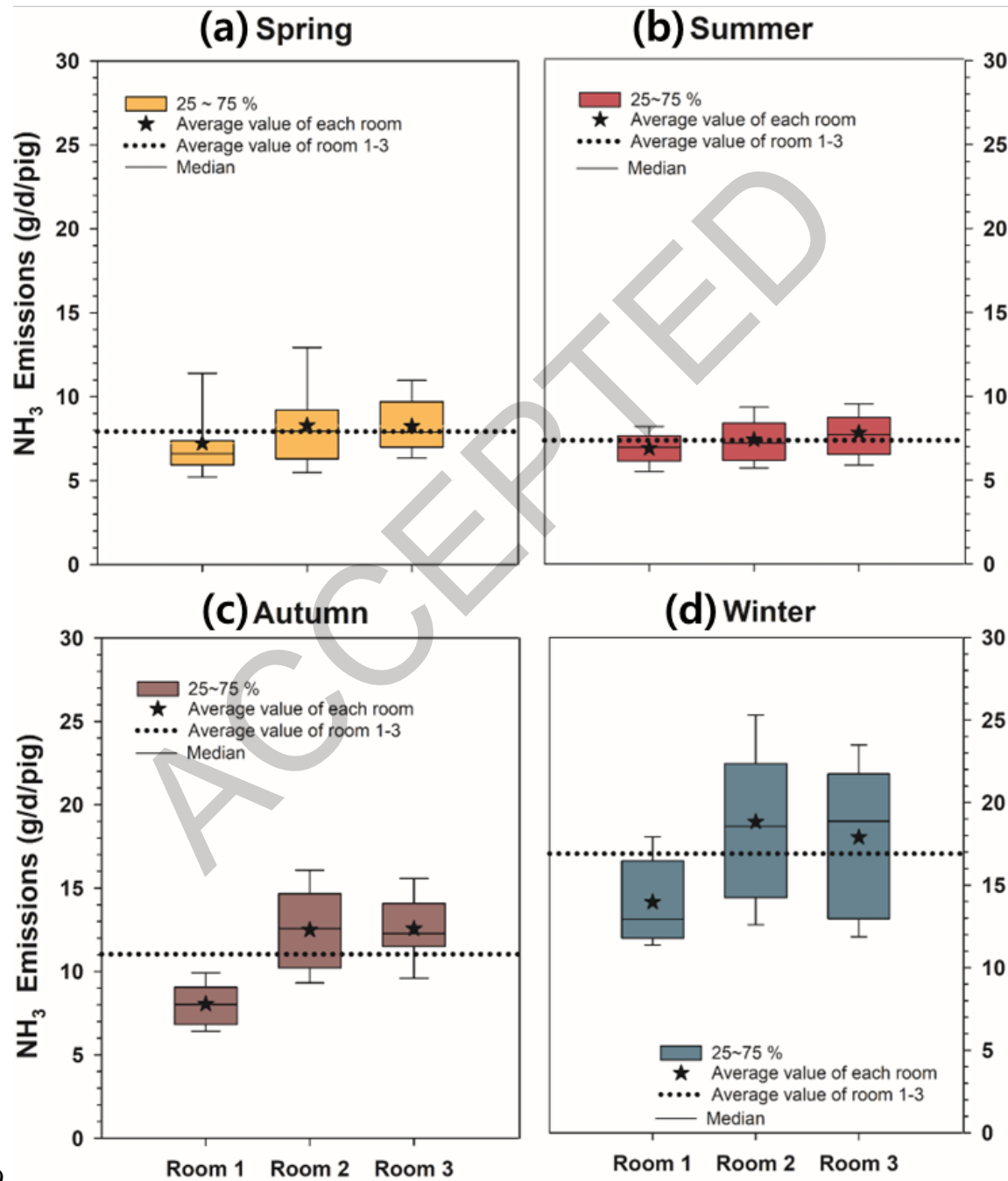


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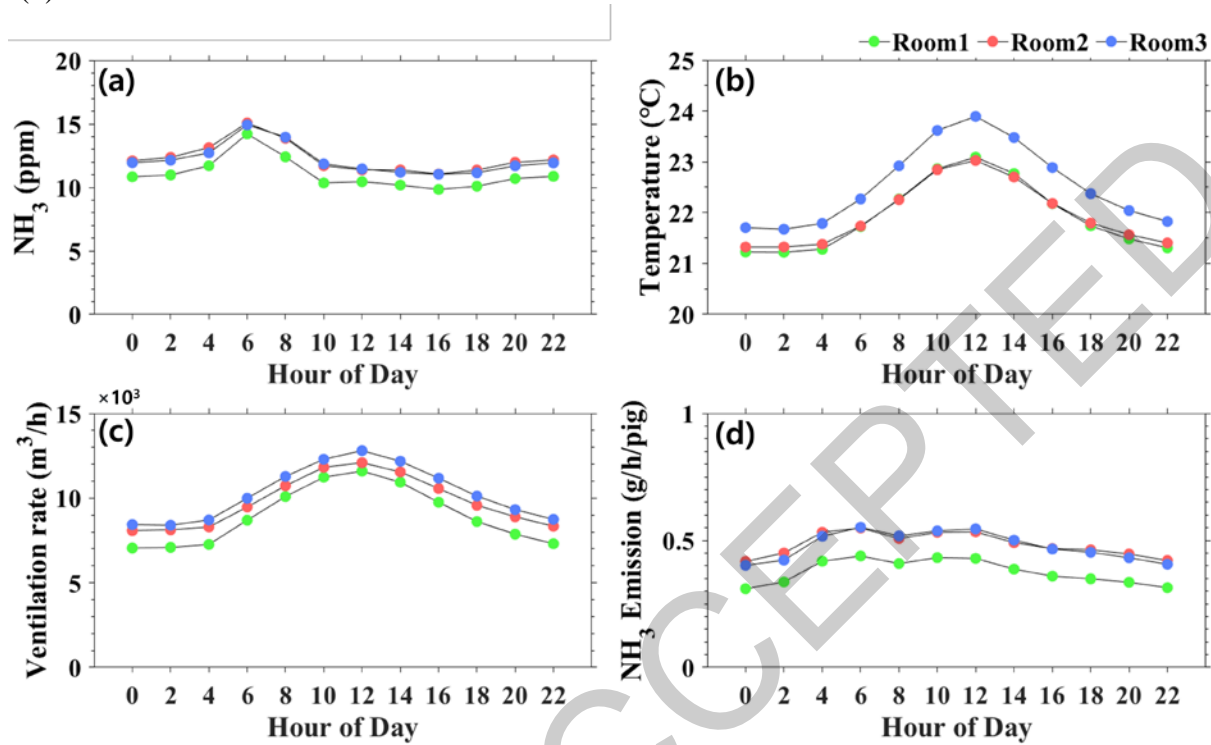
Fig. 3. Comparisons of variables averaged across sow-house rooms 1–3. (a) NH<sub>3</sub> concentration over indoor temperature for each season. (b) Relative humidity over indoor temperature for each season. (c) Monthly comparison of NH<sub>3</sub> concentration, ventilation rate, and temperature

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60. Fig. 4. Seasonal box plots of  $\text{NH}_3$  emission factors averaged for sow rooms 1–3. (a) Spring, (b) Summer, (c) Autumn, and (d) Winter



61. Fig. 5. Daily variation in the environmental conditions of rooms 1–3. (a)  $\text{NH}_3$  concentration, (b) indoor temperature, (c)  
62. ventilation rate, and (d) emission factor

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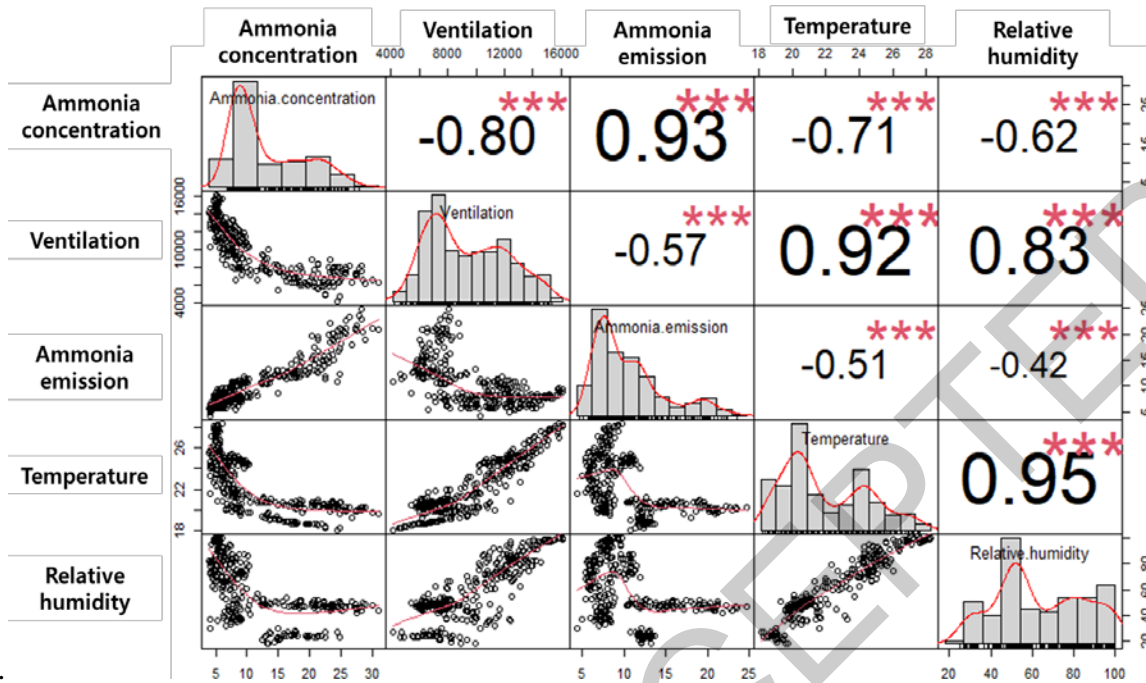


Fig. 6. Correlations for data averaged across rooms 1–3 (\* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ )

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Supplementary Material for  
Seasonal characteristics of ammonia emission in mechanically ventilated sow housing in South Korea

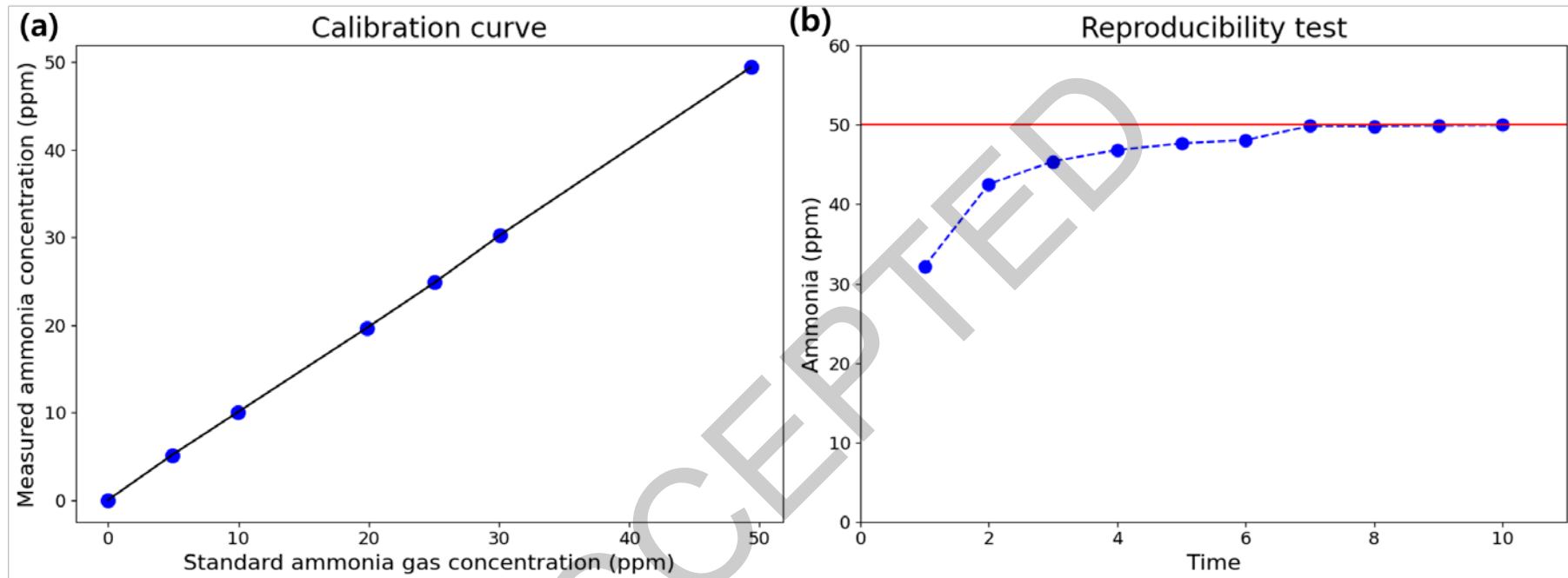


Fig. S1. Calibration curve and reproducibility evaluation of measurements using the INNOVA NH<sub>3</sub> monitoring device. (a) Calibration curve, (b) reproducibility test

Table S1. Seasonal maximum, minimum, mean, and standard deviation of NH<sub>3</sub> concentration, ventilation, indoor temperature, and relative humidity for sow-house rooms 1–3

		Room 1				Room 2				Room 3			
		Max	Min	Average	SD	Max	Min	Average	SD	Max	Min	Average	SD
<b>NH<sub>3</sub> concentration (ppm)</b>	Spring	17.5	4.2	8.3	3	17.1	3.9	9	3.1	17.7	4.2	9.1	3.3
	Summer	8.4	4.1	5.2	0.8	10.8	3.7	5.5	1.0	9.7	3.8	5.4	1.0
	Autumn	22.3	5.5	10.9	4.4	25.7	5.9	13.1	5.1	23.7	6.1	12.5	5.5
	Winter	28.2	12.9	21	3.7	31.2	14.5	23	4.2	34.1	12.9	23.2	4.5
<b>Ventilation (m<sup>3</sup>/h)</b>	Spring	12,908.3	5,869.1	8,944.7	1,642.6	13,379.3	5,419.9	9,360.0	1,775.6	13,999.3	5,640.6	9,429.5	1,952.7
	Summer	16,007.7	8,127.4	12,855.3	1,715.9	15,729.0	8,257.6	12,859.3	1,664.9	17,030.4	9,943.4	14,234.6	1,746.5
	Autumn	12,661.1	3,805.4	7,721.7	2,661.2	14,178.1	6,032.4	9,529.2	2,056.5	16,278.6	5,710.0	10,424.1	3,151.0
	Winter	9,789.3	4,186.1	6,298.3	1,028.3	10,458.0	3,881.4	7,444.7	1,273.0	10,074.8	4,279.4	7,070.8	1,214.0
<b>Temperature (°C)</b>	Spring	23.5	18.6	20.6	1.3	23.4	18.8	20.7	1.2	25	18.7	21.2	1.5
	Summer	28.1	23.0	25.4	1.2	27.4	22.3	25.0	1.4	29.5	23.5	26.7	1.6
	Autumn	24.9	18.7	22.2	1.9	25.0	20.5	22.3	1.6	26.3	19.7	22.7	2.3

<b>Relative humidity (%)</b>	Winter	21.0	18.1	19.5	0.8	21.4	18.0	19.8	1.0	20.9	18.2	19.5	0.7
	Spring	79.3	18.6	45.1	14.1	79.0	16.4	42.9	14.5	79.4	18.6	45.0	14.2
	Summer	100.0	64.1	88.1	10.2	100.0	59.7	87.5	10.9	100.0	63.8	88.1	10.2
	Autumn	87.1	47.1	64.7	12.9	87.4	39.8	62.1	15.3	87.0	47.1	64.7	13.2
	Winter	53.1	19.6	41.7	12.0	52.9	15.7	36.8	13.3	53.1	19.6	41.7	12.2

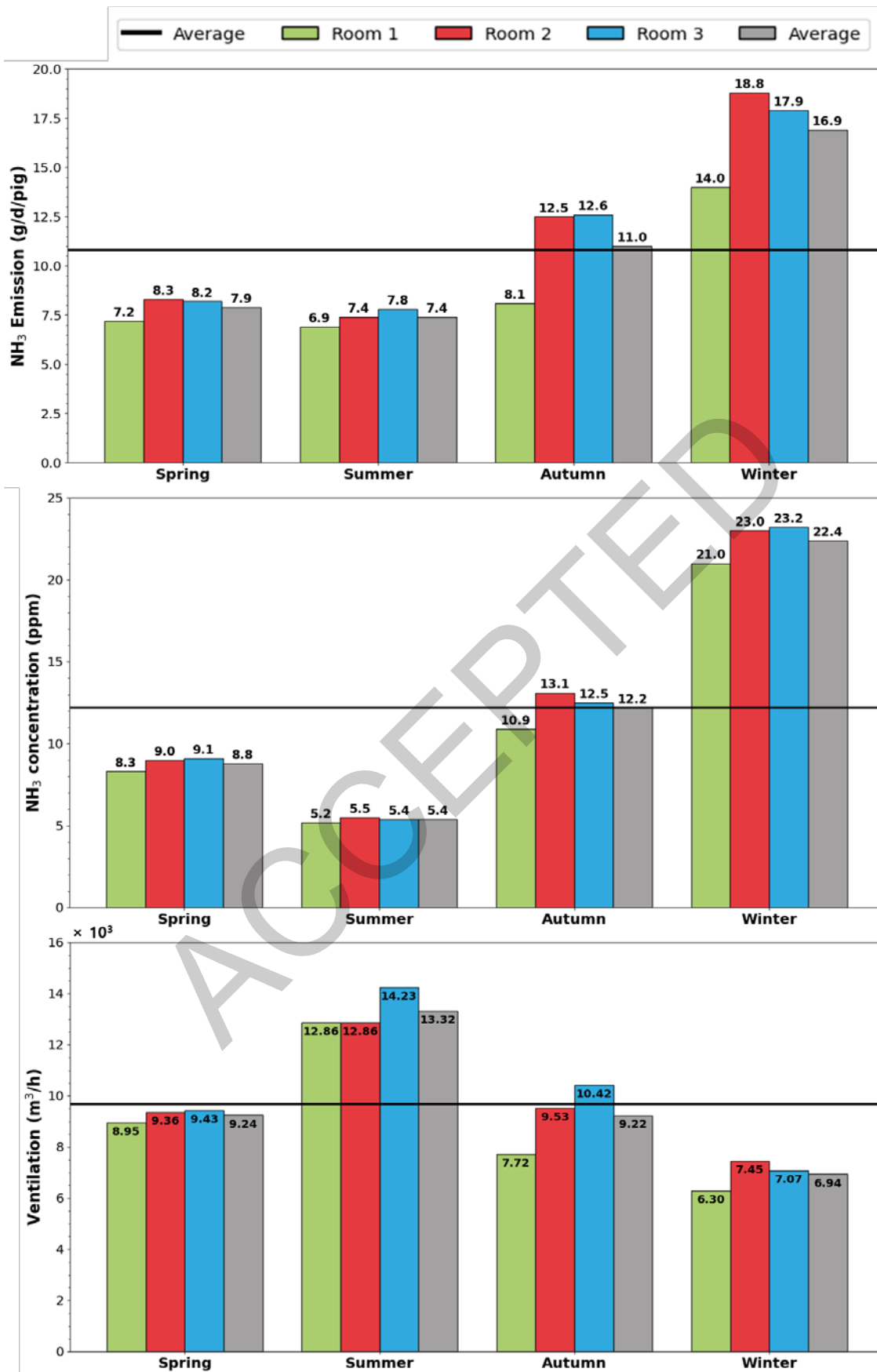


Fig. S2. Seasonal comparison of NH<sub>3</sub> emission factor, NH<sub>3</sub> concentration, and ventilation in rooms 1–3

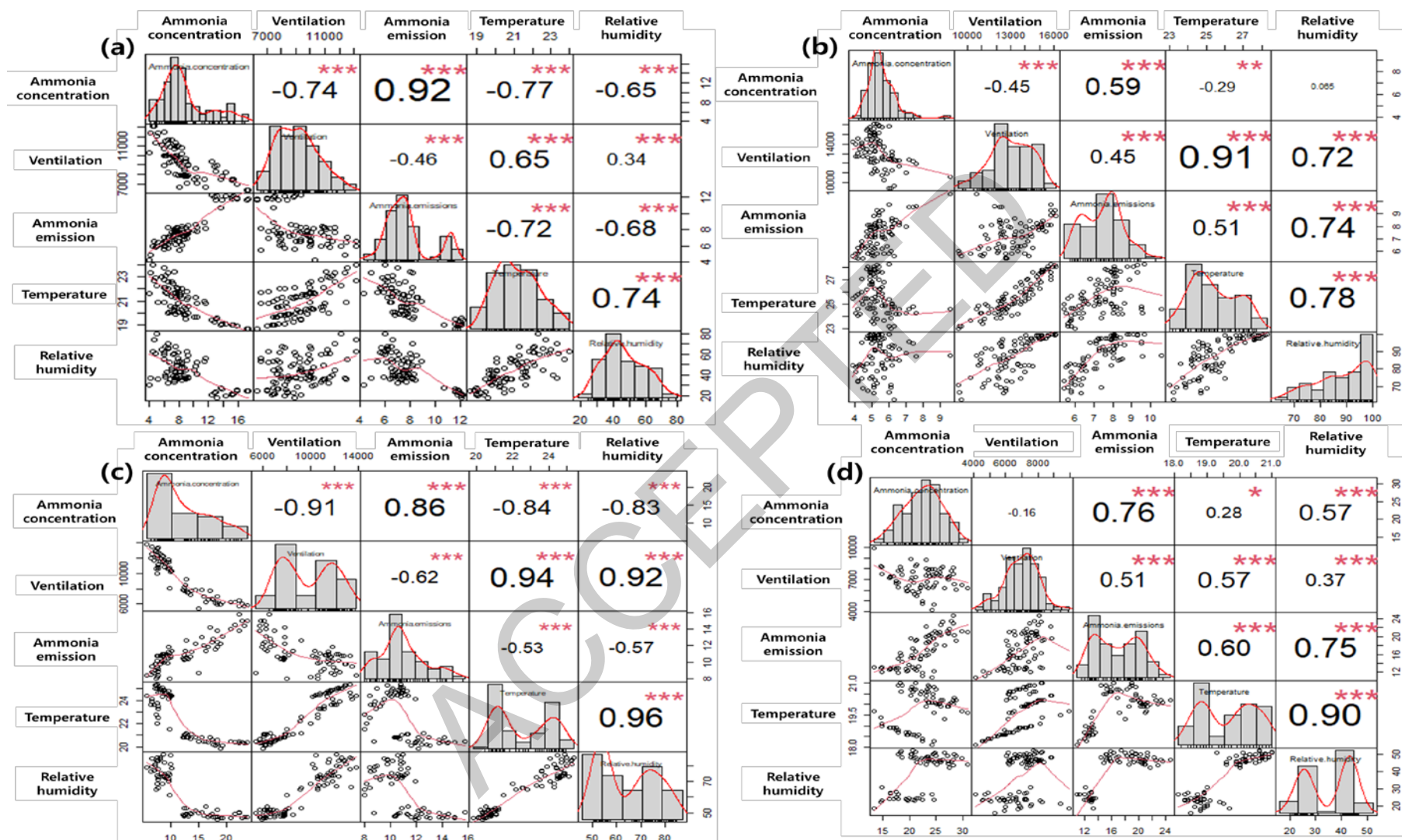


Fig. S3. Average daily correlations in rooms 1–3. (a) Spring (March–May), (b) Summer (June–August), (c) Autumn (September–November), and (d) Winter (December–February) (\* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ )

1 **Table S2.** Multiple linear regression results for predictors of indoor NH<sub>3</sub> concentration  
 2 (ventilation rate, temperature, and relative humidity) by room (Rooms 1–3)

Room	Predictor	B (Unstandardized)	SE	Beta (Standardized)	t-value	p-value	95% Confidence Interval
Room 1	(Constant)	31.125	5.220	-	5.963	<.001*	[20.854, 41.395]
	Ventilation	-0.002	0.000	-0.738	-9.935	<.001*	[-0.002, -0.001]
	Temperature	-0.293	0.355	-0.116	-0.826	0.409	[-0.991, 0.405]
	Humidity	0.017	0.031	0.057	0.540	0.589	[-0.044, 0.077]
Room 2	(Constant)	15.589	7.299	-	2.136	0.033*	[1.228, 29.950]
	Ventilation	-0.002	0.000	-0.722	-9.617	<.001*	[-0.002, -0.002]
	Temperature	1.091	0.466	0.343	2.343	0.020*	[0.175, 2.008]
	Humidity	-0.119	0.037	-0.390	-3.258	0.001*	[-0.191, -0.047]
Room 3	(Constant)	58.454	5.015	-	11.656	<.001*	[48.587, 68.321]
	Ventilation	-0.001	0.000	-0.631	-5.558	<.001*	[-0.002, -0.001]

Temperature	-2.010	0.370	-0.826	5.431	<.001*	[-2.738, -1.282]
Humidity	0.245	0.030	0.728	8.039	<.001*	[0.185, 0.305]

\* p < 0.05

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**Table S3.** One-way ANOVA comparing room-level means (mean  $\pm$  SD) of NH<sub>3</sub> concentration and environmental variables (ventilation rate, temperature, and relative humidity) across Rooms 1–3

	Room 1	Room 2	Room 3	F-value	p-value
NH <sub>3</sub> concentration (ppm)	10.96 $\pm$ 6.67	12.19 $\pm$ 7.43	12.07 $\pm$ 7.67	2.804	0.061
Ventilation rate (m <sup>3</sup> /h)	8951 $\pm$ 3069	9793 $\pm$ 2601	10281 $\pm$ 3357	18.188	< 0.001***
Temperature (°C)	21.92 $\pm$ 2.61	21.96 $\pm$ 2.35	22.53 $\pm$ 3.11	5.846	0.003**
Relative humidity (%)	61.15 $\pm$ 22.78	58.69 $\pm$ 24.34	61.14 $\pm$ 22.78	1.184	0.306

\*\*p < 0.01, \*\*\*p < 0.001

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