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An Experimental Method for Evaluating Ammonia Emission Rates of Bio-Curtain

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Abstract: Bio-curtain (i.e., curtain) is a permeable cover equipped with a spraying system for ammonia (NH_3) control in a swine facility. Previous studies investigated the NH_3 reduction effects primarily based on concentration units. It is challenging to determine the actual efficiency because of the large amount of air discharged through the large surface of the curtain, and external wind rapidly dilutes and disperses the exhausted air. Therefore, this study investigates a technique to evaluate the NH_3 reduction effect of the curtain in terms of emission rate. We constructed a metallic cover with a single hole around the curtain to gather the air discharged through it. The NH_3 reduction effect was calculated by comparing the NH_3 emission rate that was monitored in the barn exhaust fan and at the single hole of metallic cover during the non-spray and spray treatments inside the curtain at the maximum and minimum operating rate of the barn's exhaust fan. NH_3 emission rates declined both non-spray and spray at the minimum operation rate of the barn exhaust fan, but the reduction effect was higher in spray conditions than non-spray. Accumulating NH_3-absorbed water inside the curtain under the low ventilation of the exhaust fan caused these circumstances.

Keywords: ammonia; bio-curtain; metallic cover; swine facility; ventilation rate

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1. Introduction

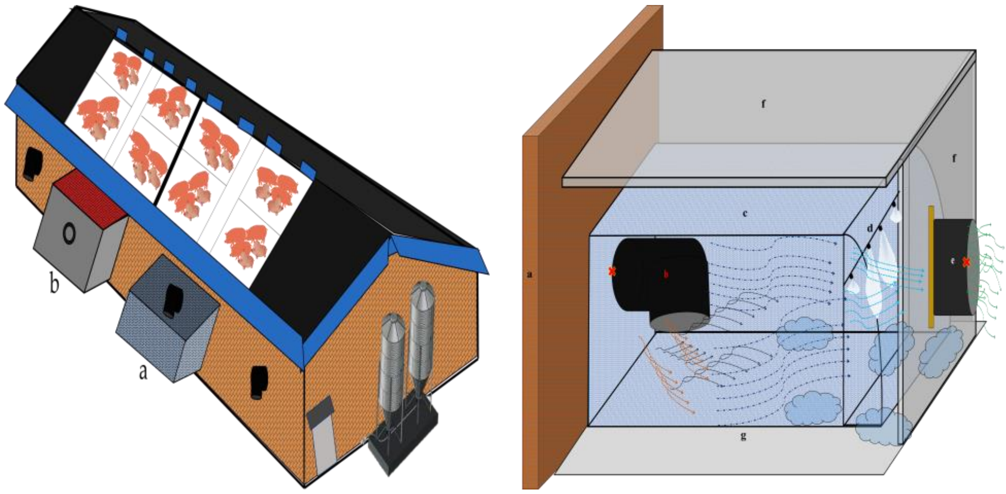
The odor emission from the swine facilities has become a major source of environmental pollution and social nuisance. Volatile fatty acids (VFAs), phenol compounds, indole compounds, ammonia (NH_3), and volatile sulfur compounds are the primary odorous substances. Among these, ammonia is the odorous compound remaining in high concentrations [1–3] and has the characteristics of high solubility in water [4,5]. In swine farms, water, microbial additive, deodorant, etc. spraying on the inside and outside air of the facilities is a method to control emissions by adsorption and dissolution of NH_3 [6,7]. The mist spraying device is also installed inside Bio-curtain (i.e., curtain) of a light shielding cover. The curtain is a known technique for reducing odor emission from swine facilities' surroundings [8]. Compared to other odor-reduction techniques, many swine farmers preferred because of inexpensive and simple to install [9]. Most of the previous studies on the curtain's odor reduction effect evaluated the reduction rate of the NH_3 concentration at a specific point outside the curtain multiple times [8–10]. However, it is challenging to determine the accurate odor concentration in the released air outside the curtain on the dilution and rapid dispersion by external winds around the curtain. As the growing awareness emphasizes the significance of accurate emission measurement, therefore, it is essential to determine, how to evaluate the effectiveness of any NH_3 reduction processes [11–13].

Therefore, to avoid the free release of the air and investigate the emission precisely, we installed a leak proof metallic cover covering the curtain to reduce the impact of external wind. Furthermore, a single air outlet hole on the front side of the metallic cover installed to measure the ventilation rate and odor concentrations discharged from the curtain in real time. Using this process, we have tried to evaluate the NH_3 reduction effect of the curtain in the viewpoint of emission rate reflecting ventilation rate rather than the conventional concentration.

2. Materials and Methods

2.1. Swine Facility and the Curtain

This study was conducted at an experimental confined swine facility with a mechanical ventilation system in the National Institute of Animal Science of Rural Development Administration, Wanju-gun, Jeollabuk-do, Republic of Korea. The ventilation system of the facility consists of a side air inlet through the building corridor and air ventilated through a 630 mm exhaust fan (model COCO-630A, Dongsung CoCofan. Ltd., Hwaseong-si, Gyeonggi-do, Republic of Korea) on the side wall (Figure 1). The curtain was constructed outside of an 8 m × 7 m dimensional animal barn with a concrete slated floor, where a total of 48 finisher pigs (average body weight 93 kg) were reared during this study period. The curtain cover was made of two layers of permeable geotextile fabric stretched over a rectangular-shaped aluminum pipe frame (H: 2.6 m × W: 4.7 m × L: 3.1 m) (Figure 2a). The distance from the barn's exhaust fan to the curtain was 1.8 m on the front sides, and the gap between the curtain and the metallic cover was 0.8 m (Figure 1b). Four spraying nozzles were installed in the upper front of the inside curtain (Figure 1b). The metallic cover with a single hole was enclosed around the curtain, and we used silicon glue to seal all gaps. This single hole was an apparatus made from an exhaust fan frame without a propeller for leading discharge air in one direction (Figure 2c).

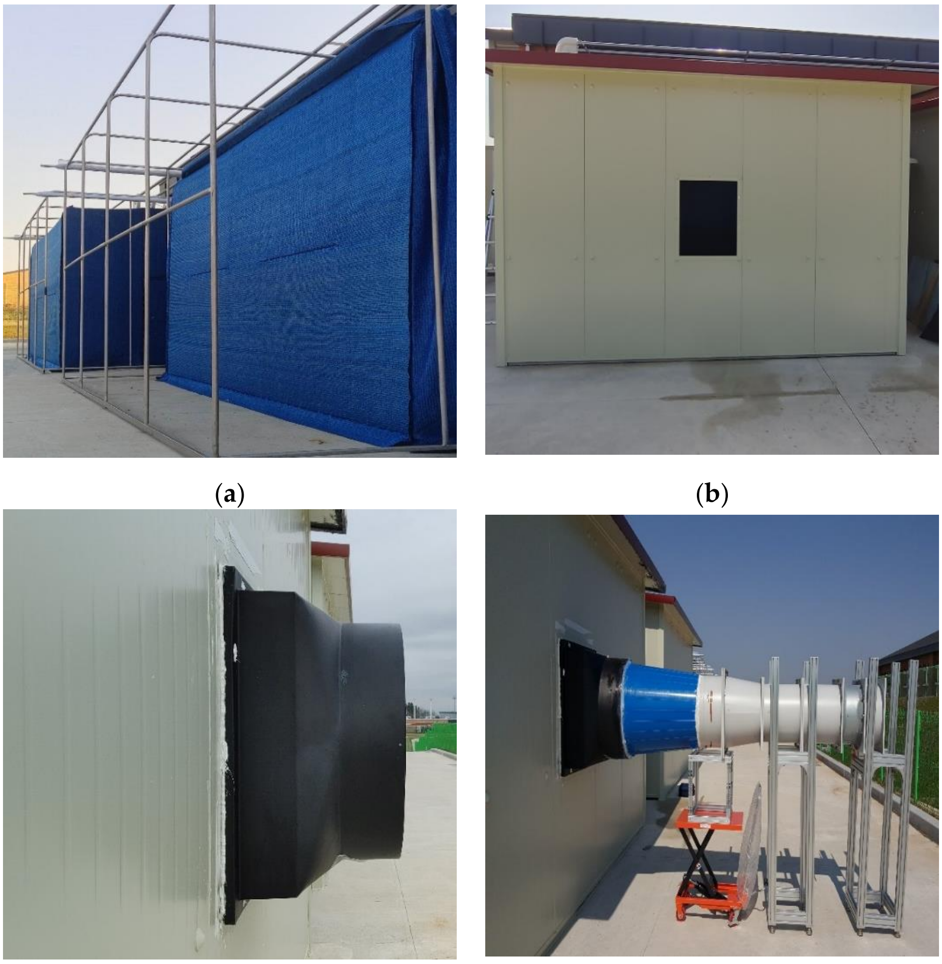


(**a**) (**b**)

Figure 1. Schematic diagram of the experimental setup, (**a**) swine facility: *a.* curtain set up, *b.* metallic cover setup, (**b**) curtain and metallic cover setup: a. barn wall, b. exhaust fan, c. curtain, d. spraying nozzles, e. single hole, f. metallic cover, g. floor, "x" markings represent the NH_3 sampling point.

2.2. Enclosing Ability of Metallic Cover

To ensure the enclosing metallic cover, we measured the air ventilation rates discharged through the swine barn exhaust fan and the single hole of the metallic cover, according to the increased operation rate of the exhaust fan (Figure 2). The airflow measurement system was designed to meet the standards of the ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) and the flow rates were measured with a micro-manometer (model: DPClaic 5825; TSI Incorporated, MN, USA). The enclosing ability of the metallic cover was evaluated as the difference in ventilation rate between the exhaust fan and the single hole.



(**a**) (**b**) (c) (**d**)

Figure 2. Curtain constructed on the outside of swine facility. (**a**) curtain, (**b**) metallic cover concealed the curtain, (**c**) single hole on the front of metallic cover, (**d**) ventilation measurement setup for air discharged through the single hole of metallic cover.

2.3. *Ammonia-Reducing Effect of Curtain*

A photoacoustic infrared multi-gas monitor (INNOVA 1512) integrated with an INNOVA 1409 (12 ports, LumaSense Technologies, Ballerup, Denmark) multipoint sampler has been used for instant analysis and measurement for the NH_3 concentration. The air sampling points were at the barn exhaust fan and the single hole of the metallic cover, respectively. The analyzing conditions are as follows: sample integration 5 s, measurement 50 s, and flushing time 11 s with continuous sampling runs the whole time. Before starting the experiment, these instruments were calibrated in the lab with the 99.999% N_2 and NH_3 standard gas. The NH_3-reducing effect of the curtain was evaluated for the two experimental conditions of non-spray and spray, respectively. Ventilation conditions of both experiments were set at 100% (maximum, 3727 m^3/h) and 30% (minimum, 891 m^3/h) for the operating rate of the barn exhaust fan. The spray conditions were divided into three treatments based on the pause times (30 min, 10 min, and 5 min), while the spray time was 10 min. The time scale for each experiment was 24 h. The NH_3 reduction was calculated as the difference in concentrations between the exhaust fan and the single hole. In addition, HOBO data loggers (UX100-011A, Onset Computer Corporation, Bourne, MA, USA) automatically log the humidity during the experimental period.

2.4. Chemical Properties of Sprayed Water

The pH, electrical conductivity (EC), total Kjeldahl nitrogen (TKN), and ammoniacal nitrogen (NH_4^+) were analyzed in tank water (before spraying) and sprayed water (during spraying). The sprayed water was collected from the floor inside of the curtain using a plastic tray and the inner surface of the curtain by attaching a wiping medium at the 30% operating rate of the exhaust fan. Because we could not collect the sprayed water at the higher operating rate of the exhaust fan by the reason as fallow: the water droplets were quickly removed out of the curtain by the high speed of exhaust fan. The chemical properties were measured by methods as follows: (1) electrode pH meter (Model 850C, Schott, Mainz, Germany), (2) EC (ES 04310.1c), (3) TKN (ES 04363.1a, ES 04363.3b), (4) NH_4^+ (ES 04355.1c, ES 04363.1a). Detailed information was reported by Hwang et al. [14].

2.5. Data Analysis

Ammonia emission rate or mass flow rate (g/h) was measured in the exhaust fan and at the single hole during the maximum (100%) and minimum (30%) ventilation, on the basis of mass balance by using the ammonia concentrations and the air flow rate (m^3/h) by using Equations (1) and (2).

$$C^{NH_3}\ (g/h) = \left[\left[\frac{M \times (17.03 \div 22.4) \times [273K \div (273K + T)]mg/m^3}{m^3/h}\right] Q(m^3/h)\right] \times 100 \tag{1}$$

$$R(\%) = \left[\left(C_{IN}^{NH^3} - C_{OUT}^{NH^3}\right) \div C_{IN}^{NH^3}\right] \times 100 \tag{2}$$

where, C^{NH3}(g/h) = mass flow rate; M = NH_3 concentrations (ppm); 17.03 = the atomic mass of ammonia; T = temperature (°C); 22.4 = The volume of 1 mol at 1 atmospheric pressure at 0 °C; Q (m^3/h) = mean flow rate; R (%) = Reduction efficiency.

3. Results and Discussion

3.1. Enclosing Ability of Metallic Cover

The NH_3 emission calculates on ventilation rate and concentration, and thus the accurate measurement of the ventilation rate is the essential factor for emission estimation [15,16]. The enclosing ability of the metallic cover is important to evaluate the amount of air exhausted from the curtain. The ventilation rate from the single hole of the metallic cover was an average of 3–5% lower than that of the barn exhaust fan according to the increase in the operating rate of the barn exhaust fan (Figure 3). In the test code for leakage by the HVAC (Heating, Ventilating, and Air Conditioning) air duct, the allowable leakage rate is 3–10% ranges for the general ventilation system [17]. Accordingly, the metallic cover had the enclosing ability to measure an accurate ventilation rate from the curtain by gathering most of the air. In addition, the ventilation rates gradually increased with a curve of a straight line (R^2 = 0.97) according to the operating rate of the barn exhaust fan as follows: 3727 m^3/h at 100%, 1383 m^3/h at 50%, and 891 m^3/h at 30% (Figure 3). It is a result of confirming that the exhaust fan is operating regularly [18,19]. However, during low ventilation operation the air velocity at the single hole got influenced by the relatively stronger external wind velocity.

3.2. Ammonia Reduction Effects in Non-Spraying Condition

The NH_3 emission rate declined at the single hole of the metal cover compared to the barn exhaust fan for both minimum (30%) and maximum (100%) ventilation rates, and the ranges were 6.6 ± 1.1 to 14.6 ± 1.1 g/h and 2.5 ± 0.5 to 4.7 ± 0.5 g/h, respectively. The reduction effect showed higher in 30% than 100% on average during non-spray treatment (Figure 4; Figure S1 in the Supplementary Materials). The major causes behind the reduction effects are two. Firstly, the meshes of curtains could capture dust/gas [10] and reduce odor in the air discharged from the barn [8,20]. In other hand, the effectiveness of odor reduction highly relates to the air retention time inside the curtain, which depends on the exhaust fan's speed or ventilation rate [10,21]. In this case, while fan speed noticeably lowered the discharged air at the minimum operation of the exhaust fan, the NH_3 emission rate also decreased than the maximum operating condition [10,22,23]. The lower airflow rate allowed the NH_3 to stay inside the curtain for a long time and thus reduced the NH_3 emission at the single hole. Also, the amount of discharged air closely relates to the NH_3 emission [24,25] and has a contradictory relationship [26,27]. Although the NH_3 concentration inside the barn decreases with the higher operating rate of the barn's exhaust fan because of the immediate removal of NH_3 by the faster fan speed [28,29], the mass flow rate (emission rate) increases in the exhaust fan [25]. Therefore, the sensors detected a higher NH_3 emission in the maximum fan operation with a higher air flow rate, but we found a considerable reduction effect during minimum fan operation because of longer air retention time and less flow rate.

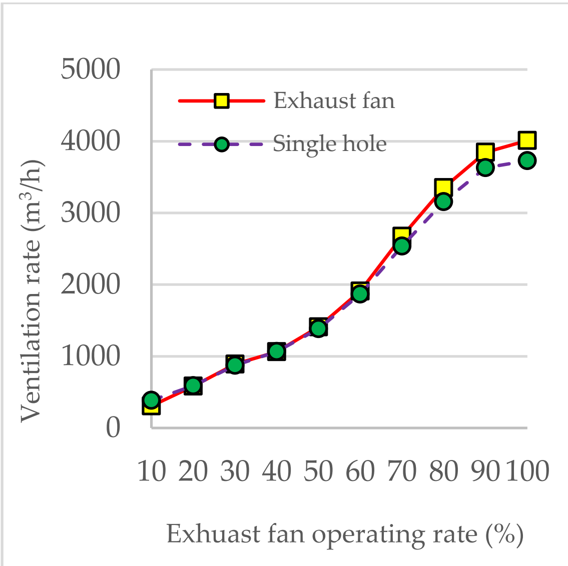


Figure 3. Enclosing ability of metallic cover.

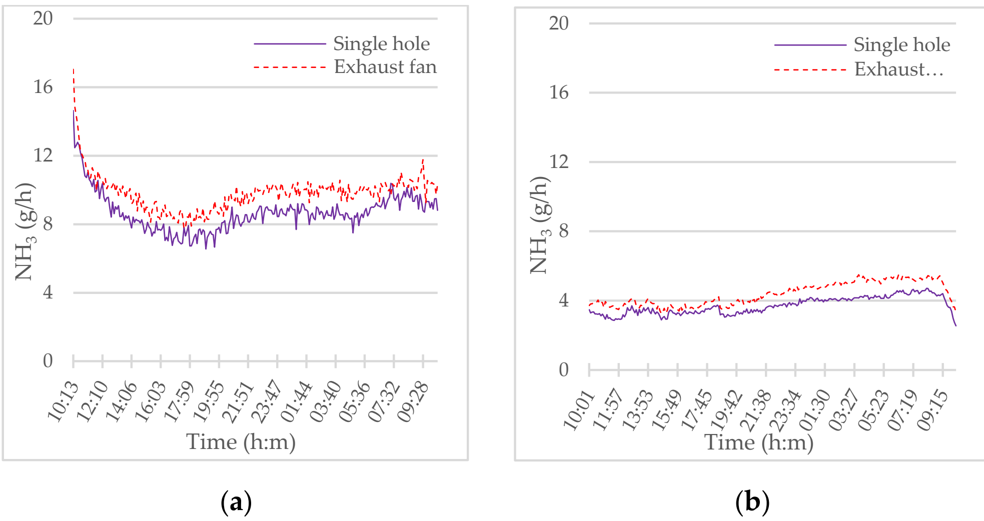
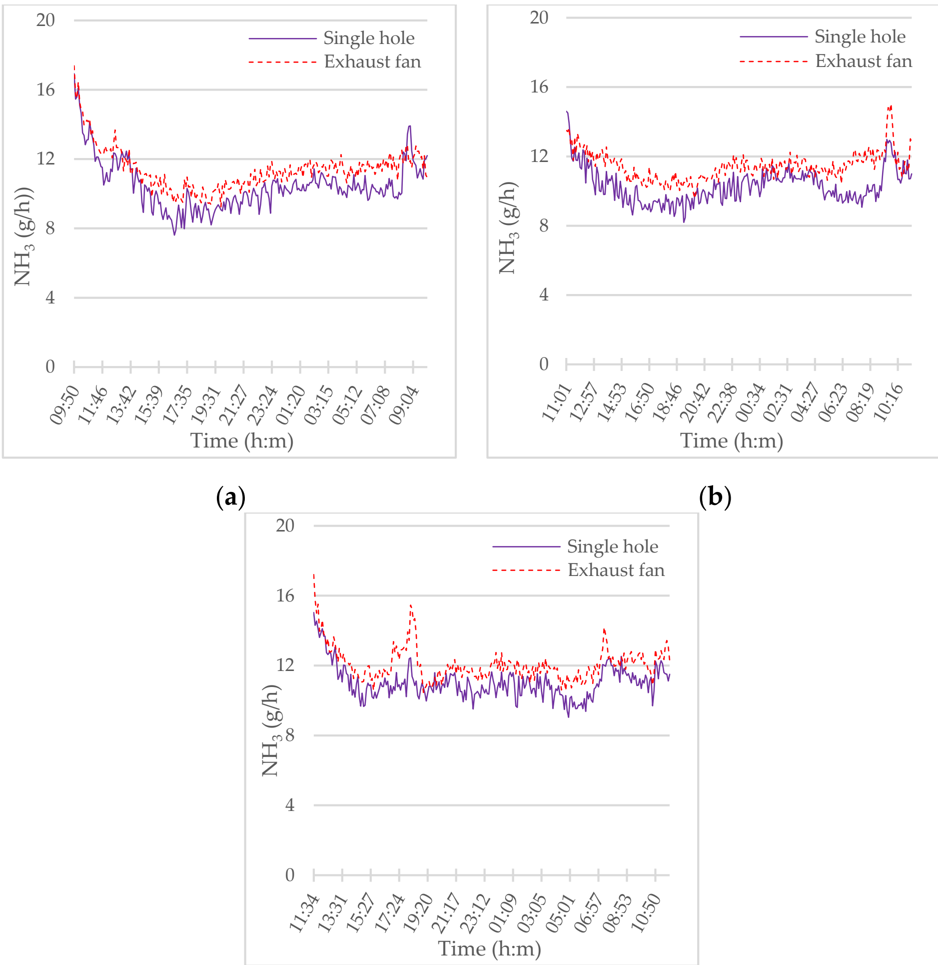


Figure 4. The ammonia (NH_3) reduction effect in non-spray conditions inside the curtain: (**a**) the maximum operating rate of the barn exhaust fan (100%), (**b**) minimum operating rate of barn exhaust fan (30%).

3.3. Ammonia Reduction Effect of Spraying Treatment Inside the Curtain

Swine farms spray water inside the curtains to increase the NH_3 reduction effect. The highly soluble characteristics of NH_3 let it get adsorbed by the sprayed water [30,31]. At the max exhaust fan operation, the NH_3 emission rate was slightly lower in the single hole than in the exhaust fan (Figure 5; Figure S2 in the Supplementary Materials). The spray treatments displayed a gradual increase in emission reduction efficiencies of 8%, 9%, and 10% (Figure 6) for S/P (spray time, min./pause time, min.) 10/30, 10/10, and 10/5, respectively. At this stage, we observed that a large amount of mist got discharged through the single hole of the metallic cover, and there was no accumulated water inside the curtain and metal cover. Because of that, the discharged air through the single hole was more humid in the spray treatments than in the non-spray [32]. The assumption was that, because of the accelerated operation of the barn exhaust fan, the absorbed NH_3 by the sprayed water quickly evaporated [33] to the outside of the single hole of the metallic cover [28,29]. In addition, the moist air would have affected some similar peak formations in the NH_3 emission rate (Figure 5). Our best guess is that the backflow and back pressure caused by maximum ventilation of the exhaust fan yielded the NH_3-enriched moist air [34,35]. Therefore, there was no notable reduction effect of NH_3 at the exhaust fan's maximum operation [36] while spraying inside the curtain (Figure 5).



(**a**) (**b**) (**c**)

Figure 5. The ammonia (NH_3) reduction effect by spraying water inside of the curtain at the maximum operating rate of the barn exhaust fan (100%), (**a**) S/P (spray time, min./pause time, min.) 10/30, (**b**) 10/10, (**c**) 10/5.

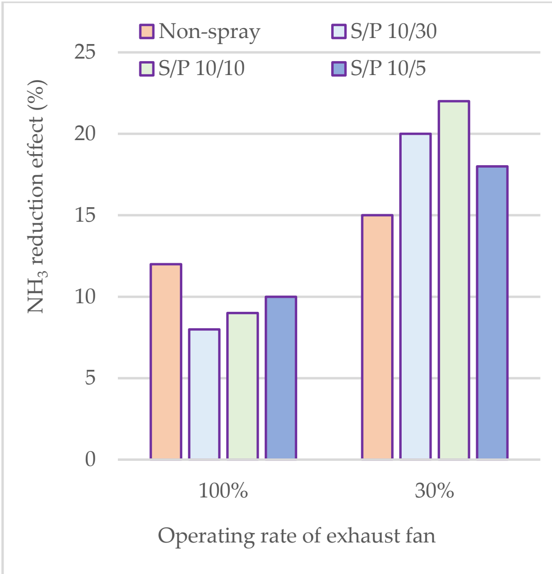
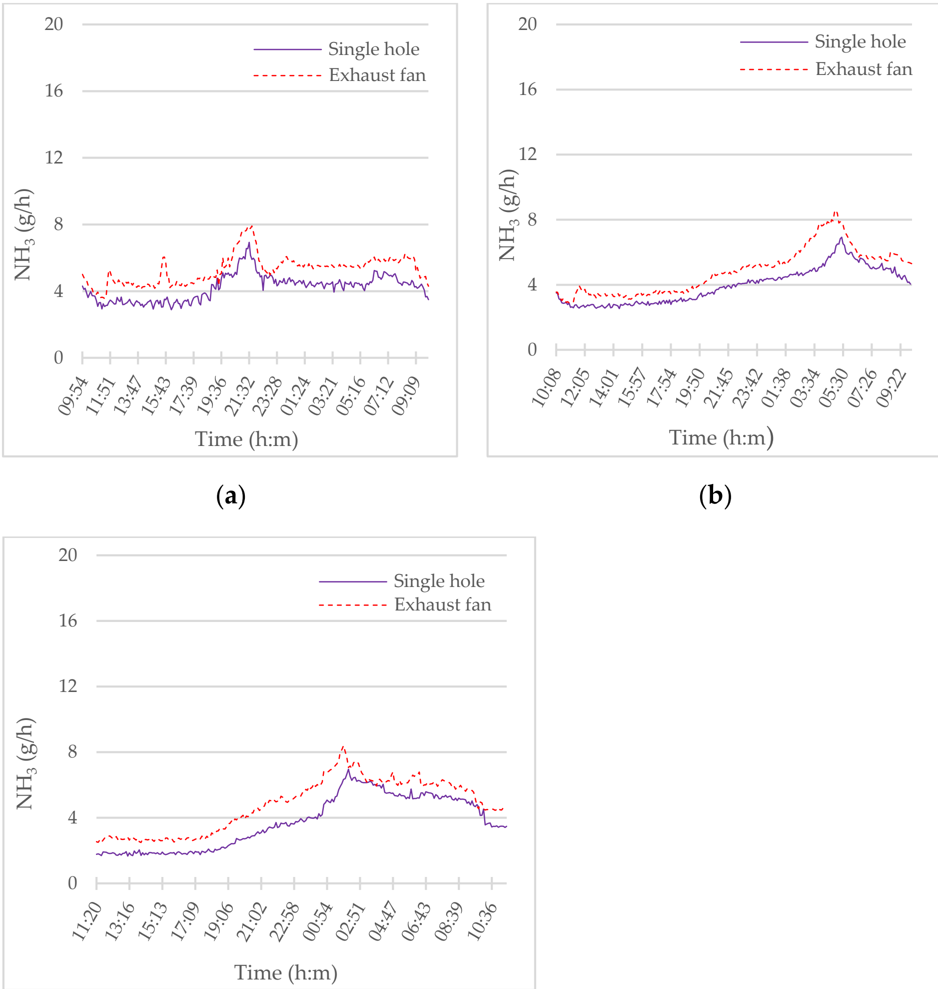


Figure 6. The ammonia (NH_3) reduction effects (%) of non-spraying and spraying water treatment. S/P (spray time, min./pause time, min.) 10/30, S/P 10/10, and S/P 10/5 at the 100% or 30% in operating rate of the barn exhaust fan.

In contrast to the above, during the minimum operation (30%) of the barn exhaust fan, the NH_3 emission rate at the metallic cover's single hole was lower in the range of 2.9 ± 0.7 to 6.9 ± 0.5 g/h, 1.7 ± 1.6 to 7.0 ± 1.6 g/h, and 2.5 ± 1.4 to 6.0 ± 1.1 g/h, correspondingly, than the exhaust fan for all three spraying treatments (Figure 7; Figure S3 in the Supplementary Materials). And the reduction rates of NH_3 emission were noticeable and higher than the non-spray as follows: non-spray (15%), S/P 10/30 (20%), S/P 10/10 (22%), and S/P 10/5 (18%) (Figure 6). Unlike the optimum operation (100%), there was no mist in the air discharged from the single hole of the metallic cover, and instead, sprayed water accumulated inside the curtain and metal cover.

We analyzed sprayed water collected from the surface and inner floor of the curtain. Ammoniacal nitrogen was only found in the water collected from the curtain-covered area but not detected in the tank water (Table 1). The water can capture NH_3 of 31% to 74% in the air [37–40], and captured NH_3 is transformed into NH_4^+ [37,38]. Ammoniacal nitrogen strongly depends on EC and TKN [41,42], and in this study, they were higher at 91% and 87% on average in collected water from curtains compared to tank water, respectively (Table 1). A high EC represents the existence and quantity of hydrogen ions, for instance NH_4^+ [40,43], and an increase in nitrogen sources escalates to TKN [44]. Because the accumulated water absorbed the emitted NH_3 inside the curtain, the NH_3 emission rates declined in all spray treatments. And also, the NH_3 emission rates showed almost stable formation between 3.7 ± 0.5 g/h to 4.2 ± 0.8 g/h. However, the S/P 10/5 treatment had the minimum reduction rate among the spray treatments of minimum fan operation, and we assumed that the frequent spraying accumulated more water and caused some secondary emissions [24,45,46]. The NH_3 reduction mechanism of the curtain-spray system follows a similar principle of a wet scrubber where NH_3 emission reduction got affected by the quality of washing water [47–49] in this case, the accumulated water. Installing a water de-accumulation hole in the metallic cover could solve this situation by discharging the hoarded water, but the ventilation rate, NH_3 concentration, and emission rate would not be measured precisely because of air leakage [50]. Put together, spraying inside the curtain reduces NH_3 emission by trapping accumulated water inside the curtain.



(c)

Figure 7. The ammonia (NH_3) emission reduction effect by spraying inside the curtain at the minimum operating rate of the barn exhaust fan (30%). (**a**) S/P (spray time, min./pause time, min.) 10/30, (**b**) S/P 10/10, (**c**) S/P 10/5.

Table 1. Characteristics of sprayed water.

Source	pH	EC (mS/cm)	TKN (mg/L)	NH_4^+ (mg/L)
Tank	7.3 ± 0.02	99.7 ± 0.6	0.005 ± 0.02	0.0 ± 2.1
Surface of curtain	7.4 ± 0.04	1252.7 ± 0.6	0.026 ± 0.10	47.0 ± 0.7
Floor of the curtain	7.6 ± 0.03	994.7 ± 0.6	0.051 ± 0.02	60.5 ± 2.1

EC, electrical conductivity; TKN, total Kjedahl nitrogen; NH_4^+, ammoniacal nitrogen.

4. Conclusions

The metallic cover installed around the curtain made it possible to measure the ventilation rates, NH_3 concentration, and emission rate in the air discharged through the curtain. This study shows that the hard metallic exterior could help to evaluate the NH_3-reducing effect of the curtain in terms of emission rate. Ammonia emission rate gets reduced highly at the minimum operating speed of the barn exhaust fan in both non-spray and spray amid low air ventilation (with NH_3 flow rate) discharged through the curtain. However, the NH_3 reduction effect had little difference among treatments and relatively had a higher NH_3 emission reduction in spraying conditions as time passed. The reason is that sprayed water inside the curtain absorbed the emitted NH_3 and accumulated inside at the lower ventilation rate, and thus the emission rate got reduced. The evaluation of the NH_3 emission rate using a metallic cover is countable for dry conditions, but for the spray treatment curtain, it became challenging to estimate the reduction effect based on NH_3 emission or mass flow rate as time passed. Therefore, this study suggests further investigation of strategies to evaluate the NH_3 reduction effect in terms of odor reduction techniques by using the spray system. In addition, to assess the NH_3 reduction effect of the spraying system inside the curtain without a metallic cover, additional research is required.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14010127/s1, Figure S1: The changes of NH_3 concentration for (a) 100% and (b) 30% ventilation in non-sprayed treatments. Figure S2: The changes of NH_3 concentration by spraying water inside of the curtain at the maximum operating rate of the barn exhaust fan (100%). Figure S3: The changes of NH_3 concentration by spraying water inside of the curtain at the maximum operating rate of the barn exhaust fan (30%).

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