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Original Article

Evaluation of Short-Term Exposure Levels on Ammonia and Hydrogen Sulfide During Manure-Handling Processes at Livestock Farms

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ABSTRACT

Background: Ammonia and hydrogen sulfide are harmful gases generated during aerobic/anaerobic bacterial decomposition of livestock manure. We evaluated ammonia and hydrogen sulfide concentrations generated from workplaces at livestock farms and determined environmental factors influencing the gas concentrations.
Methods: Five commercial swine farms and five poultry farms were selected for monitoring. Real-time monitors were used to measure the ammonia and hydrogen sulfide concentrations and environmental conditions during the manure-handling processes. Monitoring was conducted in the manure storage facility and composting facility. Information on the farm conditions was also collected through interview and walk-through survey.
Results: The ammonia concentrations were significantly higher at the swine composting facilities (9.5–43.2 ppm) than at other manure-handling facilities at the swine and poultry farms, and high concentrations of hydrogen sulfide were identified during the manure agitation and mixing process at the swine manure storage facilities (6.9–19.5 ppm). At the poultry manure-handling facilities, the ammonia concentration was higher during the manure-handling processes (2.6–57.9 ppm), and very low hydrogen sulfide concentrations (0–3.4 ppm) were detected. The air temperature and relative humidity, volume of the facility, duration of manure storage, and the number of animals influenced the gas concentrations.
Conclusion: A high level of hazardous gases was generated during manure handling, and some levels increased up to risk levels that can threaten workers' health and safety. Some of the farm operational factors were also found to influence the gas levels. By controlling and improving these factors, it would be possible to protect workers' safety and health from occupational risks.

1. Introduction

The emergence of large-scale livestock-breeding operations, such as concentrated animal feeding operation systems, can reduce the operating costs of breeding livestock and poultry, but such facilities can be sources of atmospheric emissions, including ammonia, hydrogen sulfide, volatile organic compounds, greenhouse gases (such as carbon dioxide, methane, and nitrous oxide), and particulate matter [1–5]. These external factors can directly influence the occurrence of multifactorial disease in animals and workers [6]. Livestock farm workers perform various tasks, such as caring for animals, cleaning animal pens, maintaining the breeding

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facilities, and handling manure for slurry removal. In particular, manure-handling processes, including agitation and mixing of the manure, can result in a very rapid release of odors, ammonia, and hydrogen sulfide [7–9].

Individual farming conditions and environmental factors have crucial influences on hazardous gas release [10]. To identify the influence of these factors on the gas emissions, modeling studies of gas emissions from manure-handling facilities have been recently conducted to estimate the emissions based on inputs of actual measurement data and influential parameters such as farm operation or management factors (e.g., storage type, duration of manure storage), environmental factors (e.g., air temperature, humidity), and physicochemical characteristics (e.g., manure pH, chemical reactions) [11–14].

Although several studies have assessed exposure to hazardous gases at livestock farms, most continuous emission monitoring studies have been undertaken in individual workplaces, such as inside an animal house over set periods of time. There are insufficient data available for evaluating livestock facilities and the short-term variations of potentially toxic emissions. This study measured ammonia and hydrogen sulfide concentrations emitted during manure agitation for slurry removal at the manure-handling facilities, focusing on the short-term exposure at commercial swine and poultry farms, and determined the impact of environmental factors, such as temperature, humidity, and breeding environment, on the concentrations.

2. Materials and methods

2.1. Description of sampling sites

Five commercial swine farms and five poultry farms were examined in this study (Table 1), and the manure-handling facility was categorized into manure storage and manure composting facilities. The common processes of manure handling are as follows: the manure collected from animal barns at each farm is stored at an independent site outside the barn and fermented for 2–12 months. Then, the solid manure is separated at the manure storage facility and converted into fertilizer for reuse with new litter beds at a composting facility.

The five swine farms all raised growing-finishing pigs. Swine manure collection was accomplished using a litter bedding system in three farms and a deep-pit system located under the floor of the pig building in the other two farms. The litter bed is a traditional method for manure removal and is a mixture of sawdust or wood shavings. The litter on the layer of the animal room mixed with manure is fermented and dried during the growing period of the pigs. The deep-pit manure system has become popular in recent years and consists of a deep manure pit under a fully or partially slatted floor. Manure stored in the pit for a few days is removed by pulling the pit plug and letting the manure drain into a storage compartment located outside the pig building [15].

The five poultry farms included three broiler barns and two barns with laying hens. The broiler barns used a litter bed for manure removal, which was similar to the litter bedding system used for pigs. A manure belt system was installed in the barn with laying hens, which used conveyer belts located under each row of cages to collect poultry feces. The feces collected from the conveyer belts were removed once every three days and stored in manure storage spaces located at the end of the row of cages.

The openness of facilities, as described in Table 1, was defined as follows. The "open" area was defined as a structure that was open on all sides or that had at least one side that was always open, without any covers. The "closed" area was defined as a

Table 1
General details of the selected livestock farms.

Farm*	Sampling location	Animal building					Number of workers	Manure storage facility		Composting facility
		Volume (W × L × H, m^3)	Ventilation type	Manure collection system	Animal type	Animal density (animals/m^2)		Open/closed type	Storage period (month)	Open/closed type
S1	-Manure storage -Composting	11 × 63 × 3	Natural	Litter bedding	Growing-finishing pig	0.33	3	Closed	8	Semi-closed
S2	-Manure storage -Composting	12 × 58 × 3	Natural	Deep-pit	Growing-finishing pig	0.22	3	Open	10	Semi-closed
S3	-Manure storage	16 × 84 × 3	Natural	Litter bedding	Growing-finishing pig	0.12	4	Closed	12	N/A†
S4	-Manure storage -Composting	9 × 52 × 3	Natural	Litter bedding	Growing-finishing pig	0.34	3	Semi-closed	6	Semi-closed
S5	-Manure storage -Composting	13 × 67 × 3	Natural	Deep-pit	Growing-finishing pig	0.17	4	Closed	6	Semi-closed
P1	-Manure storage	7 × 50 × 3	Natural	Litter bedding	Broiler	14.29	2	Open	3	N/A†
P2	-Manure storage	10 × 40 × 7	Natural/Mechanical	Litter bedding	Broiler	15.00	4	Open	6	N/A†
P3	-Manure storage	12 × 43 × 5	Natural/Mechanical	Litter bedding	Broiler	23.26	2	Closed	3	N/A†
P4	-Manure storage -Composting	13 × 61 × 3	Natural	Manure belt	Laying hen	4.62	5	Closed	2	Semi-closed
P5	-Manure storage -Composting	14 × 72 × 7	Mechanical	Manure belt	Laying hen	5.67	4	Closed	5	Semi-closed

* S1–S5: Swine farms, P1–P5: Poultry farms.
† Not applicable; the composting facility was empty during the survey in the S3 farm, and there was no composting facility in the broiler farms (P1–P3).

structure that was closed on all sides or had one side that was open while handling manure. The air in the latter area is not ventilated when the manure is not being handled. The “semiclosed” area was a structure that was always open on one side, and the air in this area is partly ventilated on typical days.

2.2. Gas monitoring

Gases were monitored in manure-handling workplaces, such as manure storage and/or composting facilities. Fig. 1 shows a scheme used for monitoring ammonia and hydrogen sulfide during manure-handling processes. A direct-reading multigas monitor was used to measure concentrations of ammonia, hydrogen sulfide, and oxygen (Multi-RAE Lite; RAE Systems, San Jose, CA, USA). Environmental conditions such as carbon dioxide and carbon monoxide levels, indoor temperature, and relative humidity were measured simultaneously using an indoor air quality meter (IAQ-CALC, Model 7545; TSI, Shoreview, MN, USA).

The gases were monitored at the manure storage facility and/or composting facility, as shown in Table 1. Monitoring was not conducted at the composting facility in each broiler farm because it was not constructed at the time of the study. Personal monitoring was used to measure the target gases from source areas, using a multigas monitor placed within the workers' breathing zone during the period they worked on manure-handling processes. The temporal variation in ammonia and hydrogen sulfide was logged in real time during the manure agitation and mixing processes. The instruments recorded the concentrations of the gases and environmental conditions simultaneously, and the data recording interval was set to every 30 seconds during manure agitation and mixing processes. During the sampling time, two data samples were recorded per minute, and the one datum sample indicated average concentration for 30 seconds.

As the manure-handling process is usually done for a short period of time, the monitoring was performed for 14–30 minutes. It was also considered that acute poisoning such as asphyxiation can occur in a moment at high concentrations of gas. The manure-handling processes are performed only when the manure storage or composting facility was full of manure, but the facilities were not full in the sampling period. Thus, the workers at each farm were asked to perform the processes such as manure agitation and mixing tasks using agitating devices as usual. The number of workers engaged in the manure-handling tasks actually varies every time, and not all workers at each farm perform the tasks. Thus, only one worker simulated the manure-handling processes when we investigated. The worker also did not wear any personal protective equipment as usual. In particular, the gases were monitored at three locations (front, middle, and back) along the line down the center of the animal house in the barns because there were no separate manure storage or composting facilities. The broiler barns in this study used litter beds, which were a mixture of sawdust and wood shavings; a waste removal company usually collects the old litter beds every 3–6 months and fills with new beds. The litter beds in each barn had been replaced newly about 2–3 months on average before the sampling date.

Instruments were calibrated to maintain a high degree of measurement accuracy. The multigas monitor was calibrated using fresh air and standard gases in a laboratory before and after monitoring. A standard gas mixture, including 50 ppm of ammonia, 25 ppm of hydrogen sulfide, and 20.9% of oxygen (Calgaz, Houston, TX, USA) gas, was used to calibrate the sensors as per the calibration procedures of the instrument manufacturer's manual. The multigas monitor was an electrochemical sensor type with a resolution of 1 ppm for ammonia with a range of 0–100 ppm and a resolution of 0.1 ppm for hydrogen sulfide with a range of 0–100 ppm. The IAQ-CALC monitor was also calibrated as per the manufacturer's instructions. This instrument uses a nondispersive infrared sensor for CO_2 measurement, with a resolution of 1 ppm, and an electrochemical sensor for CO measurement, with a resolution of 0.1 ppm.

To determine the influence of various factors on ammonia and hydrogen sulfide concentrations, the information on the breeding conditions (e.g., volume, number of breeding animals, openness, type of ventilation, and duration of manure storage after the last

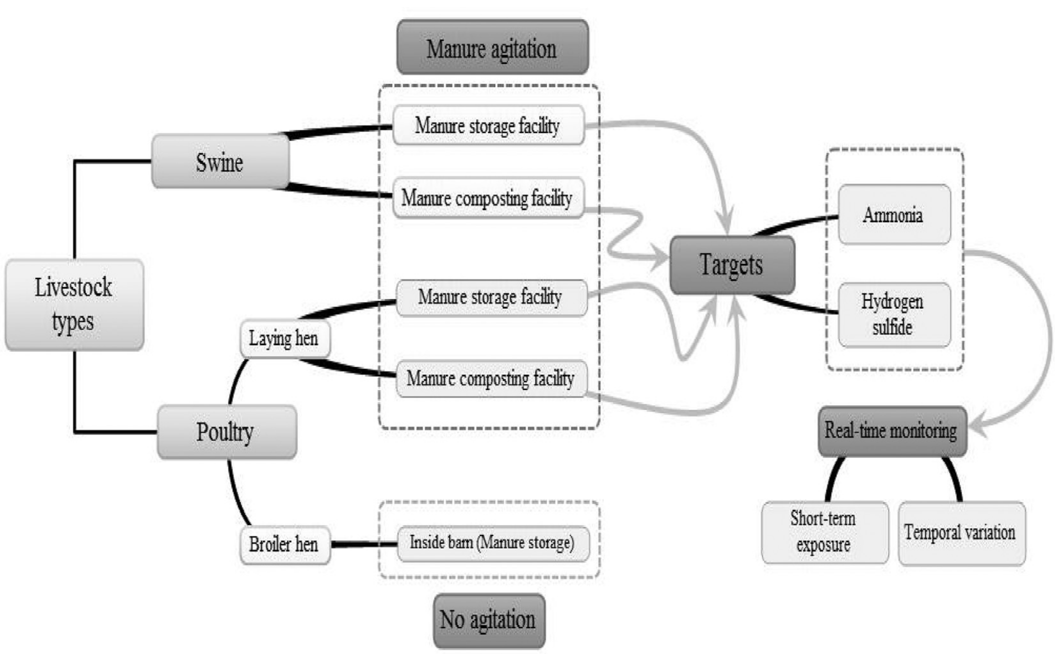

Fig. 1. The scheme for monitoring ammonia and hydrogen sulfide during the manure-handling processes.

manure removal) was collected through interviews with the owner and farm workers during the survey.

2.3. Statistical analysis

The distribution of ammonia and hydrogen concentrations was analyzed using a Shapiro–Wilk test. Because data were log-normal and skewed, log-normal transformed data were used for statistical analysis. The geometric mean (GM) and geometric standard deviation of monitoring data were used as descriptive statistics. The highest exposure concentrations of ammonia and hydrogen sulfide during the manure-handling processes were also measured.

Student t tests were used to compare the concentrations of ammonia and hydrogen sulfide between the swine and poultry farms. One-way analysis of variance (ANOVA) was used to compare the concentrations between the workplaces (i.e., manure storage and composting facilities) of each farm. Significant results from the ANOVA test were confirmed using a post hoc Tukey test. To analyze the relationships between variables and gas concentrations, a stepwise multiple regression model was used. Statistical analyses of all data in this study were performed using SAS 9.4 (SAS Institute, Cary, NC, USA), and the results were visualized using SigmaPlot 10.0 (Systat Software, San Jose, CA, USA).

3. Results

3.1. Concentrations of ammonia and hydrogen sulfide at each livestock farm

The average level of ammonia concentration was highest in farms with laying hens (GM range: 6.9–57.9 ppm), followed by swine farms (GM range: 5.9–43.2 ppm) and broiler hen farms (GM range: 2.6–8.6 ppm) (Table 2). The level of hydrogen sulfide concentration was highest in the manure storage facilities of swine farms (GM range: 6.9–19.5 ppm), followed by the composting facilities of swine farms (GM range: 0.7–4.7 ppm) and farms with laying hens (GM range: 0.7–3.4 ppm). In case of broiler farms, hydrogen sulfide was not detected.

At the swine manure storage facilities, high hydrogen sulfide levels were detected at the manure storage sites, whereas the ammonia level was higher at the composting facilities. The range of hydrogen sulfide concentrations during agitation and mixing at the manure storage facilities were more variable (0–100 ppm) than the range of ammonia concentrations (0–59.0 ppm). In particular, the hydrogen sulfide levels increased up to 100 ppm, which is the immediately dangerous to life or health value provided by the National Institute for Occupational Safety and Health during the processes. The GMs (geometric standard deviation) of the hydrogen sulfide concentration at the manure storage facilities of five swine farms (S1–S5) were 15.8 (2.9), 6.9 (2.6), 19.5 (2.2), 9.3 (3.2), and 9.7 ppm (4.1), respectively. All these levels in the swine manure storage facilities exceeded the level of 5 ppm, which is the short-term exposure limit value of the American Conference of Governmental Industrial Hygienists. The levels of the ammonia concentration (S1–S5) were 15.6 (1.4), 6.2 (1.1), 43.2 (1.1), 7.9 (1.8), and 5.9 ppm (1.9), respectively. The average short-term levels of ammonia were lower than the exposure limit value (35 ppm), but that of S3 farm exceeded the level during the processes.

At the poultry farms, the ammonia concentrations in the facilities with laying hens (P4 and P5) were considerably higher than those in the broiler hen facilities (P1–P3). In particular, the ammonia levels in the manure storage facilities of the laying hen farms were 46.4 and 57.9 ppm, respectively, and the levels

Table 2
Descriptive statistics for ammonia and hydrogen sulfide concentrations and environmental conditions.

Farm	Animal type	Sampling location*	Sampling time† (min)	N	Concentration (ppm)				Environmental conditions				
					NH_3		H_2S						
					GM (GSD)	Range	GM (GSD)	Range	CO_2 (ppm)	CO (ppm)	O_2 (%)	Temperature (°C)	Relative humidity (%)
S1	Growing-finishing pig	Manure storage	20	40	15.6 (1.4)	0.0-19.0	15.8 (2.9)	1.6-92.9	543.4 ± 65.5	1.0 ± 0.1	20.7 ± 0.3	9.2 ± 0.3	39.4 ± 2.3
		Composting	16	32	11.2 (1.1)	9.0-14.0	2.8 (1.8)	0.6-7.1	568.6 ± 123.3	1.0 ± 0.1	20.8 ± 0.1	9.6 ± 0.2	38.7 ± 1.6
S2		Manure storage	22	44	6.2 (1.1)	1.0-11.0	6.9 (2.6)	0.0-20.9	603.2 ± 76.5	1.2 ± 0.1	20.6 ± 0.2	12.2 ± 0.5	36.1 ± 1.6
		Composting	15	30	9.5 (1.1)	7.0-11.0	4.7 (1.3)	1.9-6.7	645.2 ± 82.3	1.1 ± 0.1	20.6 ± 0.1	11.7 ± 0.4	37.8 ± 0.6
S3		Manure storage	28	56	43.2 (1.1)	38.0-59.0	19.5 (2.2)	5.8-100.0	4894.4 ± 125.6	ND	19.8 ± 0.3	9.3 ± 0.6	54.5 ± 4.0
		Composting‡	N/A										
S4		Manure storage	15	30	7.9 (1.8)	1.0-16.0	9.3 (3.2)	1.1-65.8	2066.0 ± 85.3	0.1 ± 0.2	20.0 ± 0.2	11.8 ± 0.1	35.7 ± 1.9
		Composting	15	30	26.1 (1.4)	18.0-56.0	1.5 (2.0)	0.0-5.0	705.6 ± 80.4	1.1 ± 0.5	20.5 ± 0.3	10.3 ± 0.1	34.0 ± 3.3
S5		Manure storage	14	28	5.9 (1.9)	2.0-24.0	9.7 (4.1)	0.0-65.8	703.1 ± 75.5	ND	20.3 ± 0.3	8.5 ± 0.9	37.3 ± 2.6
		Composting	16	32	13.6 (2.4)	2.0-25.0	0.7 (1.3)	0.0-1.0	710.0 ± 82.9	0.2 ± 1.2	20.6 ± 0.2	9.3 ± 0.7	31.7 ± 2.5
P1	Broiler hen	Manure storage	25	50	3.5 (1.3)	1.0-12.0	ND	ND	415.8 ± 16.7	0.8 ± 0.1	19.7 ± 0.6	31.7 ± 0.6	72.2 ± 2.3
P2		Manure storage	28	56	2.6 (1.8)	1.0-15.0	ND	ND	474.4 ± 48.2	0.4 ± 0.2	20.6 ± 0.2	32.9 ± 1.3	58.8 ± 5.9
P3		Manure storage	30	60	8.6 (1.3)	2.0-16.0	ND	ND	711.2 ± 31.7	0.3 ± 0.1	20.0 ± 0.3	32.0 ± 1.8	58.8 ± 5.5
P4	Laying hen	Manure storage	19	38	46.4 (1.6)	10.0-100.0	3.4 (3.6)	0.0-42.2	437.4 ± 18.2	1.3 ± 0.1	20.7 ± 0.1	27.0 ± 0.2	93.2 ± 2.7
		Composting	20	40	35.9 (1.8)	7.0-83.0	1.7 (3.7)	0.1-20.2	485.3 ± 72.9	1.2 ± 0.1	20.6 ± 0.1	26.8 ± 0.5	90.4 ± 2.7
P5		Manure storage	16	32	57.9 (1.7)	16.0-100.0	0.7 (1.8)	0.2-1.7	678.1 ± 5.9	1.6 ± 0.4	19.3 ± 0.4	32.3 ± 1.2	56.1 ± 3.6
		Composting	28	56	6.9 (1.5)	2.0-14.0	0.9 (1.6)	0.0-1.7	604.2 ± 37.9	1.5 ± 1.1	20.3 ± 0.3	31.2 ± 1.8	60.5 ± 6.4

N, number of samples; GM, geometric mean; GSD, geometric standard deviation; ND, not detected; N/A, not applicable.GM, geometric mean; GSD, geometric standard deviation; N, number of samples; N/A, not applicable; ND, not detected.

* Manure-handling facilities such as manure storage and composting facilities. In broiler farms, the sampling was conducted in a barn because the manure-handling system was empty.

† The data were collected during manure-handling processes at each sampling location, except in broiler barns, where no manure-handling processes occurred (see Materials and methods section).

‡ There was no composting facility in the broiler barn, and therefore, sampling was not conducted. This is indicated as N/A.

exceeded the short-term limit value (35 ppm) of the American Conference of Governmental Industrial Hygienists. Although the ammonia and hydrogen sulfide concentrations were both relatively high at the swine farms, only the ammonia concentration was mainly detected at the poultry farms. Hydrogen sulfide was not detected in broiler hen farms and measured in the range from 0.7 to 3.4 ppm at the farms with laying hens.

3.2. Differences in ammonia and hydrogen sulfide concentrations based on the workplace

The monitoring results during the manure-handling processes differed among the various workplaces and types of breeding animal (swine and broiler and laying hens). Table 2 and Fig. 2 summarize the differences in ammonia and hydrogen sulfide concentrations based on the type of animals and workplaces. The concentration of ammonia differed significantly ($p = 0.04$) between the manure storage facilities and the composting facilities, and the hydrogen sulfide concentration was higher at the manure storage facilities than at the composting facilities ($p < 0.0001$). The concentrations of the two gases also differed significantly at the manure-handling facilities ($p < 0.0001$) of the farms with laying hens.

The ANOVA results in Table 3 indicate the differences among the workplaces based on the type of animals. Because the broiler farms had no composting facilities, we compared the differences between farms with swine and laying hens. The concentrations of ammonia and hydrogen sulfide during manure handling at the storage facilities were significantly different among the workplaces of each breeding type ($p < 0.0001$). During the composting process, the ammonia concentrations at the swine farm were higher than at the farm with laying hens ($p < 0.0001$), and the hydrogen sulfide concentration was also higher at the swine farms ($p < 0.0001$). Fig. 3 shows the results of a post hoc test between the individual groups, which indicated significant differences among the animal breeding types, except for the hydrogen sulfide concentrations between farms with swine and laying hens ($p < 0.0001$).

3.3. Temporal variations of gas concentrations during manure-handling processes

The gas concentrations varied during manure-handling processes such as agitation and mixing (Table 2). Fig. 4 shows the temporal variations of gas concentrations at the swine and poultry manure-handling workplaces. At a swine manure storage facility, the hydrogen sulfide level increased rapidly up to about 100 ppm during manure agitation and mixing (Fig. 4A), whereas the ammonia concentration fluctuated during work at the composting facility (Fig. 4B). The temporal variations of gas concentrations at the poultry manure-handling workplaces are shown in Fig. 4C and D. The ammonia concentrations were more variable during the manure-handling process than at the swine facilities. Fig. 4 indicates that workers could be at risk of acute poisoning from the variable gas concentrations during work.

3.4. Factors associated with gas concentrations

Table 4 shows the influence of various factors on ammonia and hydrogen sulfide concentrations using stepwise multiple regression analysis. These factors were considered to be independent variables, and the ammonia and hydrogen sulfide concentrations were dependent variables. The relationships between the dependent and independent variables at each workplace were analyzed, and the R-squared values in the model ranged from 0.29 to 0.92.

At swine manure–handling facilities, the relative humidity ($\beta = -0.01$, $p = 0.01$), open type of housing ($\beta = 0.32$, $p < 0.01$), and manure storage duration ($\beta = 0.06$, $p < 0.01$) were the factors associated with ammonia concentration. Relative humidity ($\beta = 0.02$, $p < 0.01$) and open type of housing ($\beta = 0.34$, $p < 0.01$) were also associated with hydrogen sulfide concentration. Animal density ($\beta = 0.03$, $p < 0.01$) and manure storage duration ($\beta = 165.51$, $p < 0.01$) were related to ammonia concentration, and relative humidity ($\beta = -0.03$, $p < 0.01$), animal density ($\beta = 2.08$, $p < 0.01$), and manure storage duration ($\beta = 0.20$, $p < 0.01$) were associated with hydrogen sulfide concentration at the swine composting facilities.

At the poultry manure storage facilities, animal density ($\beta = 0.25$, $p < 0.01$), open type of housing ($\beta = 5.87$, $p < 0.01$), and manure storage duration ($\beta = -1.31$, $p < 0.01$) were associated with ammonia concentration. Relative humidity was the only factor influencing hydrogen sulfide concentration ($\beta = 0.02$, $p < 0.01$). Air temperature ($\beta = 0.87$, $p < 0.01$) was related to ammonia concentration, and relative humidity ($\beta = -0.03$, $p = 0.01$) and manure storage duration ($\beta = 0.64$, $p = 0.02$) were associated with hydrogen sulfide concentration at the poultry composting facilities.

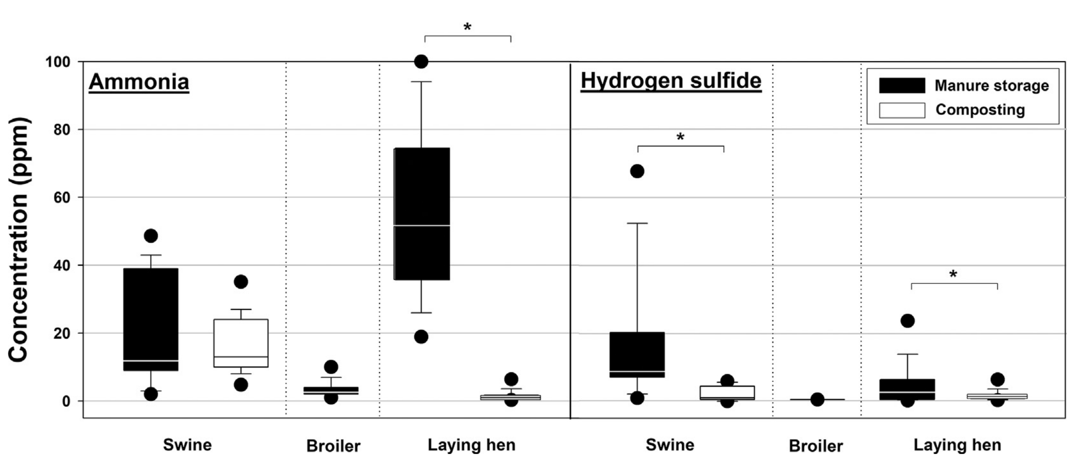

Fig. 2. Concentration of ammonia and hydrogen sulfide at manure storage facilities and composting facilities; the line values of each boxplot indicate mean (line within the box), 25th and 75th percentiles (bottom and top of the box, respectively), 10th and 90th percentiles (lower and upper bars on the whisker, respectively), and outliers (black circles). *, p < 0.0001.

Table 3
Comparison of ammonia and hydrogen sulfide concentrations during manure-handling processes in swine and poultry farms.

Type	Breeding type	Concentration (ppm)													
		Ammonia						*p*-value	Hydrogen sulfide						*p*-value
		Manure storage facility			Composting facility				Manure storage facility			Composting facility			
		N	GM (GSD)	Range	N	GM (GSD)	Range		N	GM (GSD)	Range	N	GM (GSD)	Range	
Swine	Growing-finishing	198	12.3 (2.8)	1.0-59.0	124	14.2 (1.9)	2.0-56.0	0.0446	198	11.3 (3.0)	0.0-100.0	124	1.9 (2.5)	0.0-7.1	<0.0001
Poultry	Broiler	166	3.3 (1.7)	0.0-16.0	N/A*				166	ND	ND	N/A*			
	Laying hen	70	49.2 (1.7)	10.0-100.0	96	7.1 (1.7)	2.0-83.0	<0.0001	70	2.6 (3.8)	0.0-42.0	96	1.1 (2.3)	0.1-8.9	<0.0001
ANOVA	MSE	17.9			3.6			N/A*	76.6			4.4			N/A*
	F-value	239.1			23.0				441.8			31.6			
	p-value	<0.0001			<0.0001				<0.0001			0.0109			
	R square	0.51			0.09				0.61			0.12			

N, number of samples; GM, geometric mean; GSD, geometric standard deviation; ND, not detected; ANOVA, one-way analysis of variance; MSE, mean square error, N/A, not applicable.ANOVA, one-way analysis of variance; GM, geometric mean; GSD, geometric standard deviation; MSE, mean square error, N, number of samples; N/A, not applicable; ND, not detected.

* There was no composting facility in the broiler barn, and therefore sampling was not conducted. This is indicated as N/A.

4. Discussion

Livestock workers might be at risk from environmental hazards in their workplaces, and animals also could be exposed to the hazards in their barns. This study evaluated the concentrations of ammonia and hydrogen sulfide emitted in swine and poultry farms and identified the factors influencing them. The identification and quantification of hazardous gases emitted from manure-handling process are essential to assess the work environment and to ensure compliance with regulations. The active sampling method is usually considered to be accurate and is the current standard method. However, only time-weighted average exposure levels during a certain period of work can be obtained, and it is also difficult to identify temporal variations in detail during the working day compared with real-time monitoring [16]. The real-time monitor can identify the time-dependent variation of a concentration profile and determine the duration of emission of high concentrations of gases, although there are issues of uncertainty. Recent technological advances have overcome the shortcomings of the direct-reading instruments that were used in the past. In this study, we used recently developed real-time monitors that were calibrated before each survey with known concentrations of ammonia and hydrogen sulfide. As the technical problems have been gradually resolved, real-time monitors have been used more widely to evaluate hazardous emissions in livestock farms [17–22].

There was a weak correlation between the concentration of ammonia and hydrogen sulfide, and each gas had different concentration profiles based on the farm characteristics and/or the type of the facility monitored. Ammonia concentrations were highest at the manure-handling workplaces of laying hen farms, followed by swine and broiler hen farms, whereas hydrogen sulfide concentrations were highest in the manure storage facilities of swine farms,

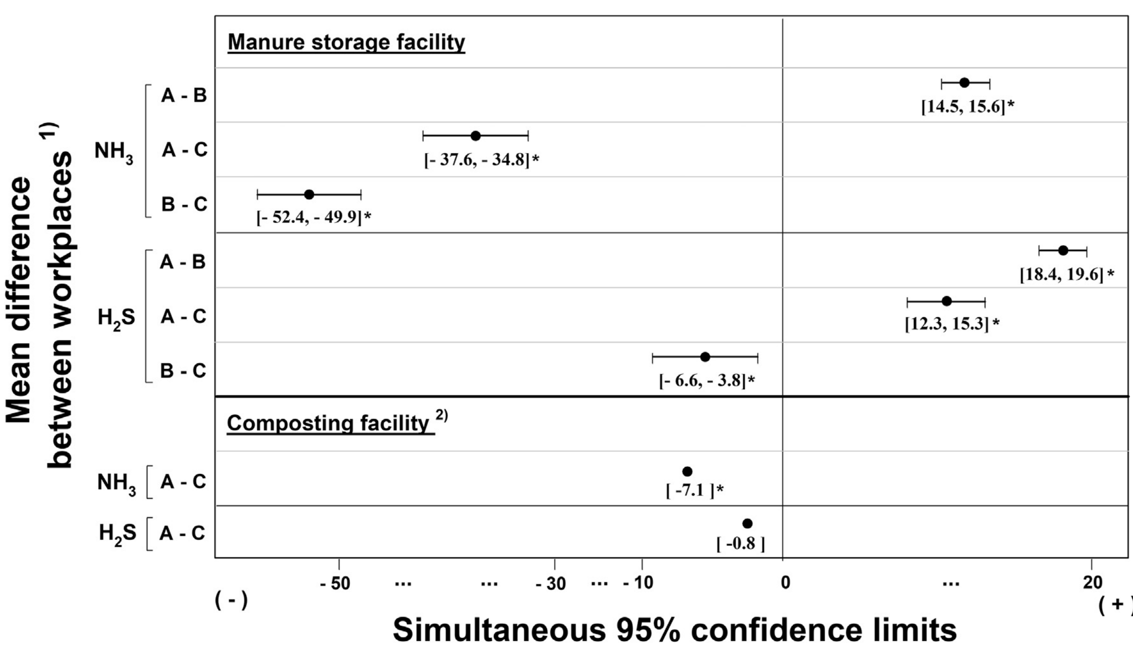

Fig. 3. Mean difference in the ammonia and hydrogen sulfide concentrations between the workplaces determined using a post hoc test. *$p < 0.05$. [1)]A: growing-finishing pig; B: broiler hen; C: laying hen. [2)]Comparison between A and C (no composting facility in broiler farms).

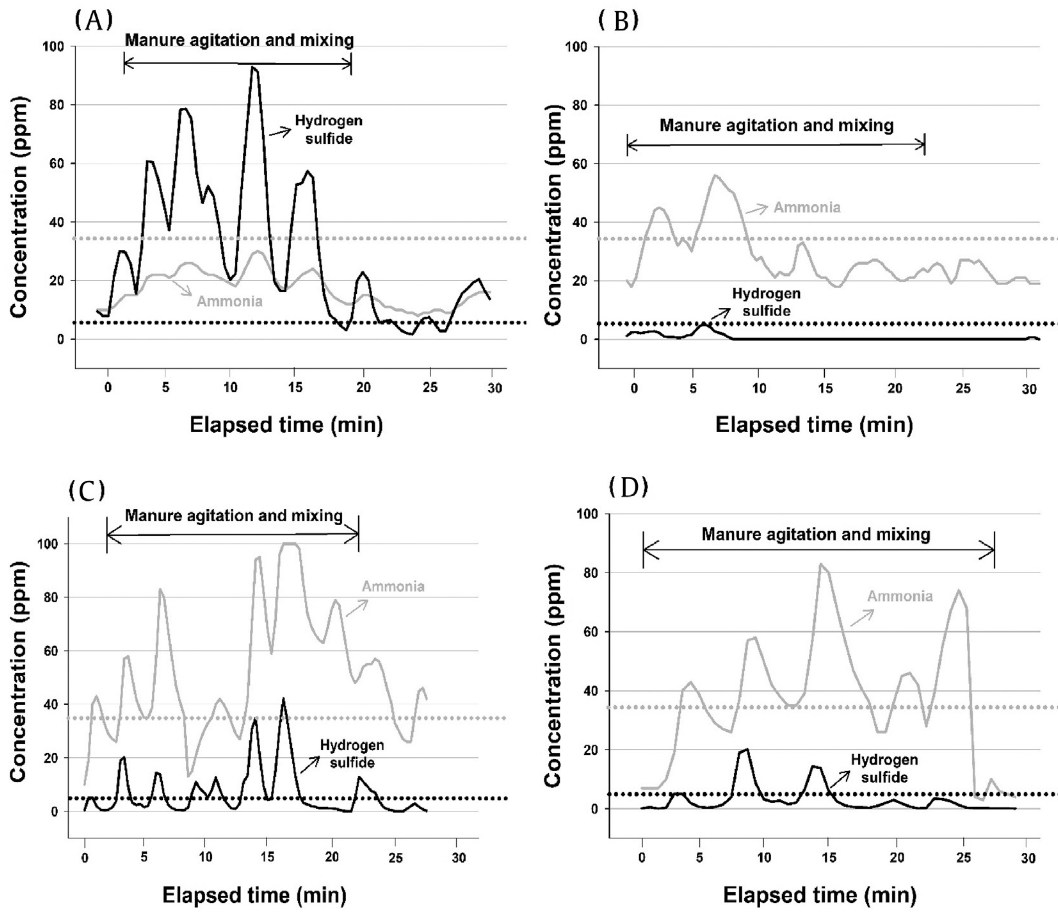

Fig. 4. Temporal variations in ammonia and hydrogen sulfide concentrations during manure-handling processes at the following facilities: (A) swine manure storage facilities; (B) swine manure composting facilities; (C) poultry manure storage facilities; (D) poultry manure composting facilities. The gray dotted line indicates the short-term exposure limit (STEL) for ammonia (35 ppm), and the black dotted line indicates the STEL of hydrogen sulfide (5 ppm).

Table 4
Factors influencing the ammonia and hydrogen sulfide concentrations.*

Type	Workplace	Target	Variable	Parameter estimate	Standard error	F-value	Significance	R^2
Swine	Manure storage facility	Ammonia	Intercept	0.26	0.07	14.15	0.0003	0.81
			Relative humidity	−0.01	0.00	6.36	0.0125	
			Open type	0.32	0.03	107.45	<0.0001	
			Manure storage duration	0.06	0.01	54.54	<0.0001	
		Hydrogen sulfide	Intercept†	0.09	0.14	0.38	0.5362	0.48
			Relative humidity	0.02	0.00	36.59	<0.0001	
			Open type	0.34	0.06	38.02	<0.0001	
	Composting facility	Ammonia	Intercept	3.31	0.10	120.32	<0.0001	0.92
			Animal density	0.03	0.15	74.57	<0.0001	
			Manure storage duration	165.51	0.00	421.98	<0.0001	
		Hydrogen sulfide	Intercept	−0.68	0.15	20.27	<0.0001	0.80
			Relative humidity	−0.03	0.01	24.02	<0.0001	
			Animal density	2.08	0.25	70.28	<0.0001	
			Manure storage duration	0.20	0.01	386.45	<0.0001	
Poultry	Manure storage facility	Ammonia	Intercept	−17.96	9.70	3.43	0.0654	0.82
			Animal density	0.25	0.13	21.80	<0.0001	
			Open type	5.87	0.03	82.03	<0.0001	
			Manure storage duration	−1.31	0.09	221.28	<0.0001	
		Hydrogen sulfide	Intercept	−1.07	0.20	28.02	<0.0001	0.39
			Relative humidity	0.02	0.00	8.71	<0.0001	
	Composting facility	Ammonia	Intercept	5.79	0.84	47.13	<0.0001	0.92
			Temperature	0.87	0.13	44.98	<0.0001	
		Hydrogen sulfide	Intercept	−8.36	4.73	3.12	0.0806	0.29
			Relative humidity	−0.03	0.01	6.96	0.0097	
			Manure storage duration	0.64	0.12	5.34	0.0230	

* Only these variables met the 0.05 significance level, .
† The model was analyzed using the "noint(no interception)" option in SAS software (version 9.4) because the parameter estimate was not significant ($p > 0.05$).

followed by the composting facilities of swine farms and farms with laying hens, and were not detected at the broiler hen farms.

As indicated in Fig. 4, the concentrations of hazardous gases are variable, and the workers could face the risk of acute poisoning if a certain limit is exceeded. A number of deaths during swine farming operations have been found to be associated with acute exposure to high levels of hydrogen sulfide [23]. The Korean Occupational Safety and Health Agency reports workplace incidents to the public. A total of nine cases involving asphyxiation at swine manure–handling facilities in the past 5 years were reported on their website. As per the details of the incidents (Table 5), the concentrations of hydrogen sulfide ranged from 68 to 470 ppm, which is a level likely to cause casualties, and a total of 15 casualties (13 deaths and 2 injured) have occurred [24].

A manure-handling facility is particularly one of the most dangerous workplaces in a livestock farm. Hoff et al. [7] conducted a study of hydrogen sulfide emissions before, during, and after the manure agitation process. The results showed that the hydrogen sulfide concentration had increased by an average of 61.9-fold relative to that before the process [7]. The results from this study also proved the aforementioned finding; high concentrations of ammonia and hydrogen sulfide could be emitted from manure-handling processes such as agitation and mixing. In this study, the mean concentrations of hydrogen sulfide ranged from 6.9 to 15.8 ppm during agitation and mixing at the swine manure storage facilities. During the processes considered in this study, the exposure levels exceeded the short-term limit value (5 ppm), and the highest concentration increased up to 100 ppm, which is the immediately dangerous to life or health value according to the National Institute for Occupational Safety and Health. The ammonia concentrations in the poultry farms investigated in this study were usually higher than those reported in other animal farms [25]. The mean concentrations of ammonia ranged from 2.6 to 57.9 ppm at the poultry manure–handling facilities and were higher than those at the swine farms. The levels were also variable, and some of them also exceeded the short-term exposure limit values (35 ppm). This phenomenon can be the result of several factors such as working manners of each worker and work environment (e.g., ventilation type, openness, and so on). After all, the most important thing is that the risk due to exposure to high levels of gas may be directly affected by factors such as whether the workers wear personal protective measures or they have recognition on the safety and health.

There are many factors influencing the ammonia and hydrogen sulfide concentrations, such as temperature, humidity, animal density, open type of housing, and manure storage duration. As the work environment is different between each individual farm, it is actually difficult to identify what factors are related to the hazardous gas emissions, but the factors were characterized from multiple regression analysis using limited data. Previous studies have also shown that as temperature and moisture level increase, ammonia and hydrogen sulfide concentrations rise [26–29]. Because these environmental factors could affect gas volatilization levels, it is important to control for a lowering of the emission rate [9,10]. In previous studies, it is well known that there are relationships between environmental factors such as temperature and humidity and the concentrations. We identified that the inverse relationship between the air temperature or relative humidity and the gas concentrations was due to the ventilation rates used for controlling the environmental conditions. However, it needs to be considered a bias by the temperature in this study because there were large differences of temperature between each measuring location. Previously, Burton and Beauchamp [30], Hinz and Linke [31], and Zhu et al. [32] also found an inverse relationship between environmental factors and gas emissions based on the ventilation rates. Through statistical analyses, we also found that the breeding conditions, including the open type of housing and animal density, and duration of manure storage were associated with target gases. In previous studies, it has been reported that the type of animal housing, ventilation rate, manure collection system, stage of production, and the breeding scale were the main variables affecting the emissions [15,21,27,33,34].

Monitoring over short time periods typically reveals only a small part of the actual emissions and cannot adequately cover diurnal and seasonal variations [21], but it can be crucial to prevent acute poisoning incidents because sudden exposure to a high concentration of a toxic substance could cause death in a short time period. This study focused on hazardous gas monitoring for short time periods, but continuous long-time monitoring is also needed to protect workers from chronic health effects due to long-term exposure. In addition to short-term monitoring for hazard identification, diurnal or seasonal monitoring data could explain variations that would provide useful information to control the work environment. It is important to conduct the work with precautionary measures in the manure-handling processes to prevent asphyxiation incidents due to acute exposure to hazardous gases. The precautionary measures would be more effective if it is difficult to implement the engineering measures immediately. Regular inspection of workplaces, identification/recognition of hazards, proper ventilation, and use of protective personal equipment are good examples of effective prevention strategies.

In summary, a high level of the gases was emitted during manure agitation and mixing processes, and the level sometimes increased up to risk levels that can threaten the workers' safety and health in a moment. It was also identified some environmental conditions can influence the exposure level simultaneously. This condition can cause unforeseen incidents such as asphyxiation due to acute poisoning; thus, it is necessary to lower the level less than

Table 5
Asphyxiation incidents due to hydrogen sulfide [24].

Case	Location	Cause	Concentration (ppm)	Death	Injury
1	Manure removal tank	Acute poisoning	74 (Stage 1) 470 (Stage 2)	2	–
2	Manure storage facility	Acute poisoning	440	1	–
3	Manure storage facility	Acute poisoning	154	1	–
4	Manure storage facility	Acute poisoning	68	2	–
5	Manure storage facility	Acute poisoning	80	2	1
6	Manure storage facility	Acute poisoning and fall	Not provided	1	—
7	Manure storage facility	Acute poisoning	212	2	1
8	Manure removal tank	Acute poisoning	74	1	—
9	Manure storage facility	Acute poisoning	273	1	

at least permissible exposure limit values and to check the environment periodically. Considering the outcomes, it is important to control the working environment with the precautionary measures to prevent the unexpected incidents due to acute exposure to high levels of gas.

Conflicts of interest

All authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2019.12.007.

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