# Production of ammonium sulfate fertilizer using acid spray wet scrubbers

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**Abstract:** Ammonia emissions are significant nitrogen losses from animal facilities that result in severe environmental problems. Meanwhile, maintaining the supply of nitrogen (N) fertilizer for crop production becomes challenging due to the unsustainable method of commercial N production that uses natural gas as the primary feedstock. This study investigates an alternative method for production of ammonium sulfate (AS) fertilizer using acid spray wet scrubbers. Ammonium sulfate is the main byproduct of mitigating ammonia emissions from animal production facilities using acid spray wet scrubbers, in which dilute sulfuric acid ($H_2SO_4$) reacts with ammonia-laden air from exhaust fans of animal facilities. Effluents of two acid spray scrubbers, one installed at a deep-pit swine facility (with a sizeof0.16 $m^3$, empty bed residence time of 0.57 s, and maximum loading rate of 1028 $m^3$/hr) and another one at a commercial poultry manure composting facility (with a sizeof 4.06 $m^3$, empty bed residence time of 0.69 s, and maximum loading rate of 24000 $m^3$/hr), were analyzed for their characteristics and AS fertilizer contents. Short-term batch operation of the swine and poultry scrubbers resulted in effluents with maximum AS concentrations of 18.7% (g/ml) and 36.3% (g/ml), respectively. Aside from AS, other essential elemental contents were also found in the scrubber effluent, such as Na, Mg, Al, P, K, Ca, Fe, and Mn. Production rates of AS were calculated based on nitrogen mass balance analyses of air streams and were compared to actual production observed during the scrubber operations. The maximum AS production rates were estimated as 1.53 kg/d and 60.96 kg/d for swine and poultry operations, respectively. However, only 0.28 kg/d and 19.7 kg/ d were obtained from actual operation. This discrepancy was primarily due to estimation errors and liquid losses from leakage, salt precipitation inside the scrubber during short-term batch operation, and air entrainment. The estimated production costs for both swine and poultry scrubber operations based on the estimated production rates were $5.74 and $1.11 per kg pure AS, respectively. Further studies that will improve scrubber design to eliminate leaks and to operate continuously are needed to increase AS yield and profitability of the process.

**Keywords:** Acid spray scrubbers, ammonia, ammonium sulfate, animal production facilities, nitrogen fertilizer, wet scrubber effluent

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## 1 Introduction

Acid wet scrubbers have been proven effective to mitigate ammonia ($NH_3$) emissions from exhaust air streams of animal facilities (Melse and Ogink, 2005; Manuzon et al., 2007; Hadlocon et al., 2014a). Two of the common types of wet scrubbers used for animal feeding operations (AFOs) are packed-bed and spray scrubbers. Packed-bed scrubbers are commonly used in Europe due to their high efficiency for absorption. However, technical problems involving dust particles that cause clogging in the packing materials lower its efficiency. High pressure drop was also encountered by Melse and Ogink (2005), which accounted for 130% increase in power consumption upon scrubber installation. Spray

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scrubbers are found to be promising for applications in U.S. animal facilities (Hadlocon et al. 2014b; Hadlocon et al. 2014bc), where large axial fans are typically used to exhaust large quantities of indoor air with very limited capability to overcome high air resistance or pressure drop. Spray scrubbers have simpler design that utilizes the surface area of the liquid droplets as interface for chemical absorption, and thus providing low resistance to air flow. Meanwhile, acid wet scrubbers can also generate nitrogen (N)-rich effluents that can be used as liquid fertilizer for field crop production, which can be marketed as a valuable and income-generating product. The advantage of the wet scrubber technology to produce these effluents makes its long-term operation economically feasible.

Nitrogen fertilizers are commonly manufactured by fixation of nitrogen molecules ($N_2$) into anhydrous $NH_3$ molecules using natural gas such as methane ($CH_4$). This chemical process that utilizes natural gas to synthesize $NH_3$ is known as Haber-Bosch process (also Haber process), which has been the main chemical N fertilizer source for field crops. As the natural gas price increases, this non-renewable source of N fertilizer will inevitably become expensive and limited. A more sustainable method for fertilizer production is thus needed.

Ammonia is also the main raw material to derive different forms of N fertilizers such as urea (45-46% N), ammonium nitrate (34% N), and ammonium sulfate (21%). Among these N fertilizers, ammonium sulfate (AS) with chemical formula $(NH_4)_2SO_4$is a good source of both nitrogen (N) and sulfur (S). This water-soluble inorganic salt can also be used as an agricultural spray additive for pesticides, herbicides, and fungicides. The application of AS to most soils causes little or no surface volatilization loss, although it has acidifying potential and requires much lime to neutralize (Vitosh et al., 1995).

Absorption of $NH_3$ in exhaust air streams using dilute liquid sulfuric acid ($H_2SO_4$)solution is the main process behind the acid spray wet scrubber operation. This process produces effluents that contain AS,which is a form of nitrogen fertilizer. Because the use of acid spray scrubbersis a new method to produce AS, analysis and characterization of the effluents are needed to investigate its applicability and quality for use as fertilizer, means of utilization, and the economic feasibility of this fertilizer production method. This analysis would also help assess the sustainability and economic justifiability of the scrubber technology for application in animal facilities, which is currently challenged because of its high investment and operational costs.

This study aimed to characterize and quantify effluents generated from the operation of acid spray wet scrubbers for recovery of $NH_3$emissions from mechanically ventilated animal facilities with a goal to properly utilize the effluents as nitrogen fertilizer for sustainable agriculture. The specific objectives are to (1) chemically quantify the fertilizer contents (NPK) and other elemental contents of the effluent using analytical methods, (2) quantify the production rates of AS from the scrubber operation, (3) model the effluent production as a function of key factors, and (4) explore the utilization of the effluents in agriculture based on the characterization analyses.

## 2. Materials and methods

### 2.1 Principles behind acid spray wet scrubbers

Wet scrubbers are devices that use a liquid (scrubbing) solution to absorb pollutants from an air stream. When dilute acidic solution is used, absorption is further enhanced by chemical reaction. Figure 1 shows a simplified wet scrubbing process operated in counter-current mode using dilute acidic solution as the scrubbing agent. The $NH_3$-laden air reacts with $H_2SO_4$ solution of controlled pH to produce AS. The drain solution is recycled back to the tank and pumped into the spray nozzles until the liquid tank is concentrated with AS. The overall balanced chemical reaction for the production of AS under highly acidic conditions is given by Equation 1:

$$2NH_3 + H_2SO_4 \xrightarrow{\text{yields}} (NH_4)_2SO_4 \qquad (1)$$

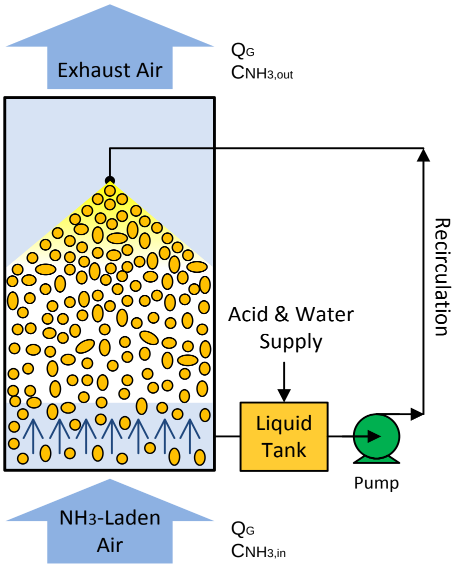


Figure 1 A simplified schematic of a counter-current acid spray scrubber with recirculation.

### 2.2 Acid spray scrubbers for animal facilities

Two full-scale acid spray scrubbers (Hadlocon et al., 2014a; Hadlocon et al., 2014b), installed on the exhaust fans of a deep-pit swine facility and a commercial poultry manure composting facility in Ohio, United States were used to produce AS fertilizer in this study. The deep-pit swine facility has a maximum capacity of 1,000 pigs, aging six weeks to five months. The facility was equipped with a total of six pit fans that were operated continuously at a constant airflow rate. Two tunnel-ventilated compost houses received manure from four manure-belt layer houses with a total of 0.83 million laying hens. The compost house where the scrubber was installed has four 122-cm exhaust fans, and the other one has eight 122-cm fans. Comprehensive details on the design and operation of these scrubbers were presented in previous studies of Hadlocon et al. (2014b, 2014c).


(a) (b)

Figure 2 Actual photographs of scrubbers installed on the exhaust fan of (a) a deep-pit swine facility and (b) a poultry manure composting facility.

### 2.3 Closed-loop wet scrubber operation and sampling of the effluents

Figure 3 shows the sample schematic of the closed-loop scrubbing process for animal facilities. The summary of the configurations and performances of each scrubber is shown in Table 1.The scrubbing liquid in the main tank was circulated through the scrubber with pH control and water replenishment to maintain a tank volume of 568 L and 1514 L for the swine and poultry farm applications, respectively. Three 200-ml samples were drawn from the hose line before the feed tank every three days for the swine scrubber and two days for the poultry scrubber. Samples were stored in ice coolers during transportation to the lab for analysis and were stabilized to freezing temperature until analyses were conducted.

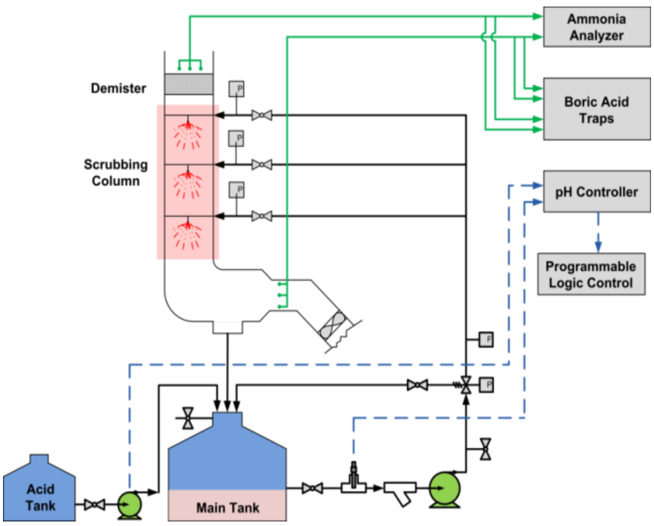


Figure 3 A schematic of the closed-loop wet scrubber operation.

**Table 1 Summary of scrubber configuration and performance.**

| Parameters | Swine Scrubber | Poultry Scrubber |
|---|---|---|
| No. of spray stages | 3 | 3 |
| Nozzle used | 3 AAP01 | 45 PJ40 |
| Liquid-to-gas ratio | 2.10 x 10-4 | 2 x 10-4 |
| Air speed | 2.87 | 0.91-2.78 |
| Air flow rate (m$^3$/hr) | 1028 | 6802-20726 |
| Nozzle pressure (MPa) | 0.34 | 0.57-0.61 |
| Liquid flow rate (L/min) | 3.6 | 44-54 |
| Liquid pH | 1.5-2 | 1.5-2 |
| Static pressure drop (Pa) | <15 | <25 |
| Efficiency (%) | 82-99 | 70-80 |
| Inlet $NH_3$ concentration (ppm$_v$) | 42154 | 100-400 |
| Minimum empty bed residence time (s) | 0.57 | 0.69 |
| Size of scrubbing section (m$^3$) | 0.16 | 4.06 |

### 2.4 Analytical analyses

#### 2.4.1 Ammonium content determination

The effluents generated from the scrubbers were analyzed for $NH_3$ (or $NH_4^+$) concentration using Salicylate method with the aid of HACH spectrophotometer. In this method, the $NH_3$ compounds reacted with chlorine to form monochloramine, which then reacted to salicylate to produce 5-amonisalicylate. This product was catalytically oxidized with sodium nitroprussideto generate a blue-colored compound. The excess reagent has a yellowish color that masks the blue color to give a green-colored solution. The color of the solution was then measured by the spectrophotometer at 655 nm. The spectrophotometer used has a precision of 38.1 to 41.9 mg $NH_3$-N/L with a sensitivity of 0.312 mg $NH_3$-N/L. The high range of measurement is 0.4 to 50.0 mg $L^{-1}$ $NH_3$-N.

#### 2.4.2 Measurement of pH and conductivity of the effluents

The pH of the scrubbing liquid or the swine scrubber operation was controlled and monitored using a pH controller and transmitter (PHCN-961, Omega Engineering, Inc., Stamford, Conn.) that can display pH values from -2 to 16 with an accuracy of ±0.01 pH. The instrument can be operated from -10 ℃ to 50 ℃. The data were obtained from the 4 to 20 mA analog output of the controller using an Onset data logger. The sensing electrode for pH is an in-line flat surface electrode (PHE-5460, Omega Engineering, Inc., Stamford, Conn.) that can be used at temperatures from 0 ℃ to 88 ℃ and up to pressure of 100 psig. For the poultry scrubber operation, a Multi-Parameter Controller (Signet 8900, Georg Fischer Signet LLC, El Monte, CA) was used to control pH that displays pH readings between -2.00 to 15.00 pH. An in-line bulb electrode was used (3 KΩ, PT1000, Signet DryLocTM pH 3-2776, Georg Fischer Signet LLC, El Monte CA), which was appropriate for corrosive applications. Due to the probes' exposure to acidic conditions, they were calibrated weekly. The pH probes were calibrated with pH 4 and pH 7 standard buffer solutions based on the guidelines provided by the corresponding manufacturer. The effluent liquid samples were also brought to the lab for verification pH measurement. Measurement of pH for these samples was done with a bench-scale pH meter (Thermo Fisher Scientific, Hannover Park, Ill.), and the values were compared with the above pH monitoring measurement for precision.

The conductivity probe (CDTX-45P, Omega Engineering Inc., Stamford, CT) used in this study has four electrodes to compensate for fouling effects. It has an accuracy of ±3% of the span (± 0.1 μS) and a response time of 12 s. It was connected to a separate transmitter (CDTX-45, Omega Engineering Inc., Stamford, CT) with 4–20 mA output that could display the range of conductivity values from 0.0 to 2000 mS. Conductivity measurements were also verified in the lab using a hand-held conductivity meter (Orion 3 Star, Thermo-Scientific, Inc., Beverly, Mass.) that displays readings between 0 to 3000 mS cm-1 with accuracy of 0.01 μS/cm.

#### 2.4.3 Elemental content determination

Effluents were also analyzed for presence of trace elements and heavy metals. Inductively Coupled Plasma Mass Spectrometry or ICP-MS (Agilent 7500 Series

ICP-MS, Agilent Technologies, Santa Clara, CA) was the method used for elemental determinations, which combined an ICP with a mass spectrometer. The sample was introduced into ICP plasma as an aerosol by reacting the sample with concentrated $HNO_3$, then feeding it to a microdigester (MarsXpress, CEM, Charleston, WV) for an hour. The samples were converted into ions and brought into the mass spectrometer via the interface cones.

### 2.5 Mass balance of AS production

Nitrogen balance analysis of air stream going through the scrubber was performed to estimate the production of AS fertilizer of each scrubber using parameters ofairflow rate, inlet and outlet $NH_3$ concentrations, scrubber efficiency, and duration of the scrubber operation (Equation 2):

$$C_{AS} = 1.2 \times 10^{-4} * Q * C_{NH_3} * \eta \qquad (2)$$

where$C_{AS}$ is the collectionrate of ammonia nitrogen in the form of ammonium sulfate (AS) in kg/d;$Q$ is the flow rate of air flowing through the scrubber in $m^3$/hr;$C_{NH_3}$ is the inlet air $NH_3$ concentration in $ppm_{v;}$ and$\eta$ is the scrubber $NH_3$collection efficiency in %.

It was assumed that the difference in $NH_3$contents in the inlet and the outlet airstreams of the scrubbers refers to the amount of $NH_3$ that was absorbed in the effluents of the scrubbers. The volumetric flow rate of $NH_3$was converted to its mass flow rate. The mass flow rate of AS was calculated based on stoichiometry, and the result would represent the production rate of AS. The AS collection rate was also compared to that obtained from the actual amounts and concentration of AS in the scrubber effluents.

### 2.6 Data analysis

The data were analyzed using JMP 9.0 Statistical Analysis Software (SAS Institute, Inc., Cary, NC) for general descriptive statistical analysis, analysis of variance (ANOVA), t-test for paired comparisons, and Tukey-Kramer's honest significant difference (HSD) for pair wise mean comparisons at 95% confidence interval.

## 3. Results and discussion

### 3.1 AS concentrations of effluents from the scrubber operations

Table 2 summarizes the generated AS solution from the operation of the swine scrubber during four seasons of a year. Results showed that the maximum concentration was achieved during winter operation, giving an AS concentration of 18.7% (g/ml) after running the scrubber for 42 days with a mean inlet $NH_3$ concentration of 25 $ppm_v$. This was followed by an effluent with AS concentration of 9.0% (g/ml) generated during summer that lasted for 28 days for an inlet $NH_3$ concentration of 11 $ppm_v$. Spring operation resulted into low AS yield of 4.5% (g/ml),because of low inlet $NH_3$ concentrations (5 $ppm_v$) observed during this period that essentially lowered the total ammonium captured. During autumn, failure of the pump seals caused noticeable leaks in the scrubber (Hadlocon et al., 2014b), and the AS concentration quantified during this period was only 4.8% (g/ml).

**Table 2 Ammonium sulfate generated from swine scrubber operation.**

| Sampling Event | Days of Operation | Inlet Ammonia Concentration ($ppm_v$) | pH | Conductivity (mS/cm) | Ammonium sulfate (%, g/ml) |
|---|---|---|---|---|---|
| Summer | 28 | 11 (±3) | 0.9 | 220.4 | 9.0 (±0.3) |
| Autumn | 19 | 23 (±11) | 1.7 | 110 | 4.8 (±0.6) |
| Winter | 42 | 25 (±6) | 1.4 | 124.5 | 18.7 (±0.1) |
| Spring | 32 | 5 (±2) | 1.2 | 135.1 | 4.5 (±0.1) |

Table 3 summarizes AS solution obtained from the poultry scrubber operation. The highest concentration of 36.3% (g/ml) was achieved during the summer with run duration of 14 days and a mean inlet $NH_3$ concentration of 113 $ppm_v$. During winter operation, the effluent reached an AS concentration of 32.5% (g/ml) from a test duration of 17 days with an average inlet air $NH_3$ concentration of 139$ppm_v$. During spring and autumn operation the scrubber was run at a shorter length of 9-10 days due to maintenance issues in the pump, which resulted in effluent solutions of 18.3-22.0%(g/ml) AS.

**Table 3 Ammonium sulfate generated from poultry scrubber operation.**

| Sampling Event | Days of Operation | Inlet Ammonia Concentration ($ppm_v$) | pH | Conductivity (mS $cm^{-1}$) | Ammonium sulfate (%, g $ml^{-1}$) |
|---|---|---|---|---|---|
| Winter | 17 | 139 (±64) | 1.5 | 119 | 32.5 (±0.1) |
| Spring | 10 | 110 (±46) | 1.5 | 127.8 | 22.0 (±0.1) |
| Summer | 14 | 113 (±12) | 1.7 | 160.2 | 36.3 (±0.1) |
| Autumn | 9 | 113 (±33) | 1.6 | 126.5 | 18.3 (±0.1) |

### 3.2 pH of the effluents

During the scrubber operation, pH is a critical factor that needs to be maintained between 1.5 and 2(Hadlocon et al., 2014a) for maximum $NH_3$ absorption. The pH was maintained well for both swine and poultry scrubber operations, which resulted in pH ranges of 0.9-1.7 and 1.5-1.7, respectively. For the swine scrubber operation, manual addition of acid due to malfunctioning pH control caused pH to reach lower values down to 0.9.

Based on the pH results, the effluent will not need any other major post-processing, but require basic additive to neutralize the acidic nature of the solution for direct land application as liquid nitrogen fertilizer. Typical pH values of commercial AS fertilizers range from five to seven. Therefore, the low pH of the scrubber effluent needs to be adjusted by addition of lime. This is currently in practice in the U.S. when AS is used as a fertilizer. Therefore, we do not foresee a major post-processing of the effluents for use as fertilizer through land application.

### 3.3 Elemental contents of the effluents

In addition to the N content, the effluent was also analyzed for other elemental contents. Most metals found in both effluents are Na, Mg, Al, P, K, Ca, Fe, and Mn. Figure 4 illustrates the mean concentration of the elemental content of the swine and poultry effluents. The most abundant elements present in the effluent from the swine scrubber operation are Mg, with an average concentration of 418.97 (±133.74) mg/L, and Ca, with an average concentration of 384.03 (±103.31) mg/L. For the effluent from the poultry scrubber operation, the trace elements are relatively low compared to the concentration observed from the swine effluent.Ca is the major element, with an average concentration of 187.77 (±37.84) mg/L, followed by Na, with an average concentration of 152.37 (±70.94) mg/L. For both effluents, Na, Ca, and Mg are the major trace elements present, which are part of the micro or macronutrients needed by animals. Furthermore, these elements are commonly used as amenders for the solubility of Phosphorus in water to improve water quality during run-off (Moore and Miller, 1994). Mostly, the elements dissolved in the solution are the ones highly soluble to sulfate solution. These results confirmed that there is no any other toxic or harmful substance in the scrubber effluents and the scrubber effluents are safe to be used as liquid fertilizer.

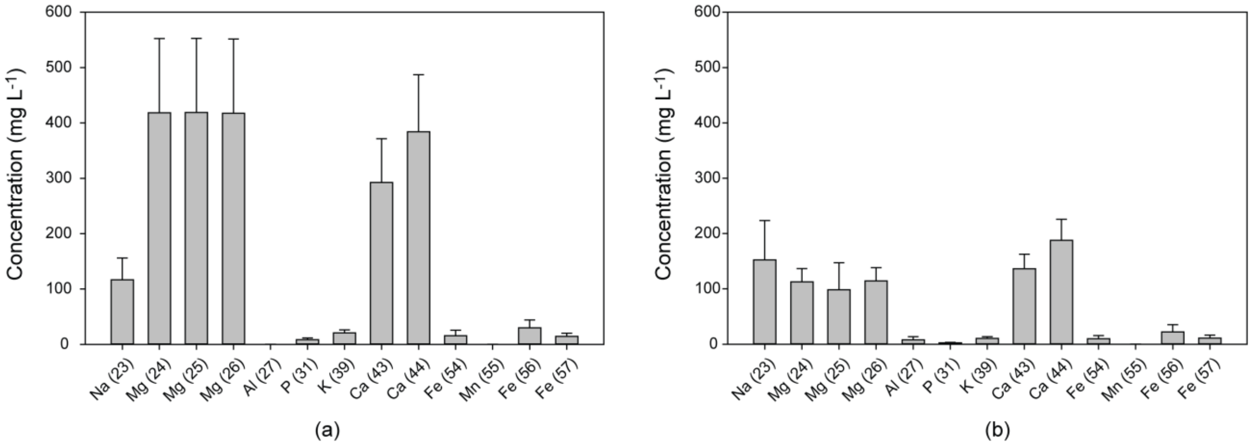


Figure 4 Average concentration of the dissolved metals found in terminal effluents of (a) the swine scrubber and (b) the poultry scrubber.

### 3.4 Production of the AS Solution

Figure 5 shows the progression of the concentration of AS as the scrubber was continuously operated. For swine operations (Figure 5a), the scrubber tank was maintained at a constant volume of 568 L, while for poultry operations (Figure 5b), the tank volume was maintained at 1514 L. During the stable operations of the scrubbers, pH was controlled to range between 1.5 and 2.0, while the conductivity increases over time due to an increase in ion concentration inside the scrubbers. Conductivity reflects both the acid and AS concentration in the scrubbers. Maximum conductivities achieved were 220.4mS/cm and 160.2mS/cm for swine and poultry scrubber operations, respectively. However, for swine operations, conductivity values tend to go higher due to excess in the acidic ions added when manual control of pH was conducted.

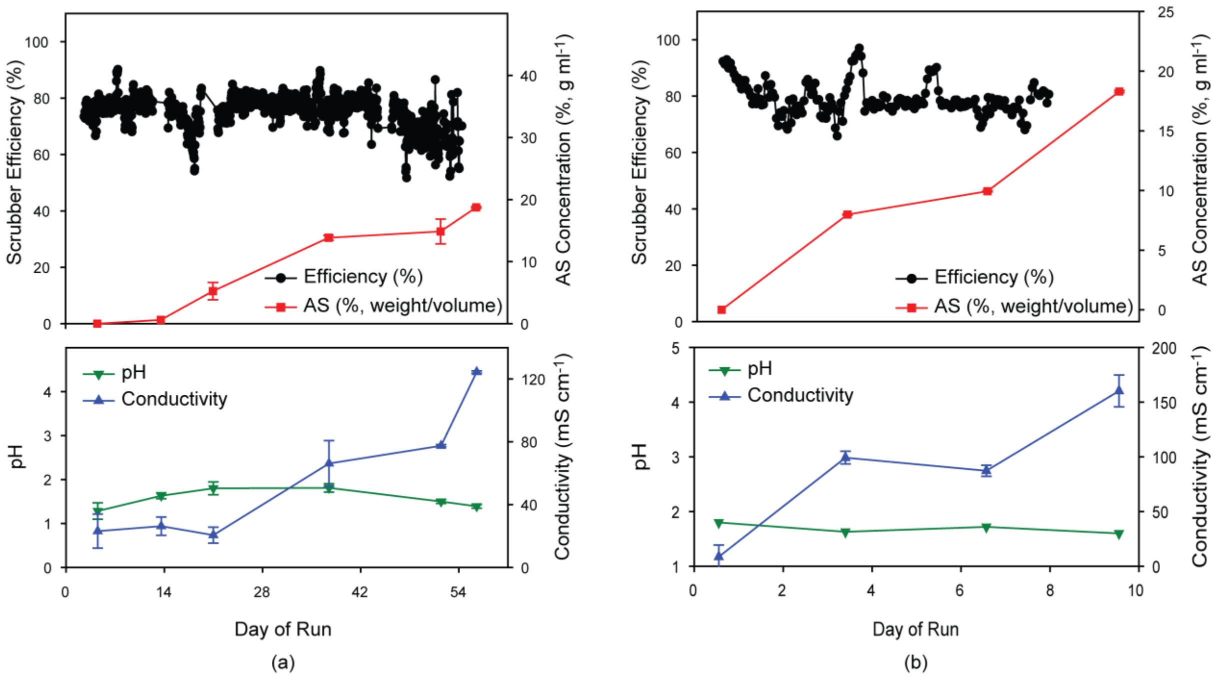


Figure5 Variations of the scrubber efficiency, ammonium sulfate concentration, liquid pH, and conductivity during operations of (a) the swine scrubber and (b) the poultry scrubber.

There is a strong linear correlation (R = 0.85) between AS concentration and conductivity as shown in Figure 6.The regression model predicted that the conductivity at 30% (g/ml) AS was about 159 mS/cm ($R^2$ = 0.73).This correlation suggests that the conductivity of the scrubber solution under stable and continuous operation can be used as the control parameter to indicate the saturation point of the AS production process using acid spray wet scrubbers. The conductivity observed in the field showed deviations from conductivity obtained from lab simulations. Variations of conductivity in the field were due to dynamic changes in the tank contents where consistent evaporation and replenishment of water in the scrubber tank were being done. Variations can also be accounted to imperfect mixing in the tank. Additional error can be attributed to the change in temperature at the field sites, which can affect conductivity of the liquid as it could shift equilibrium reactions in solutions.

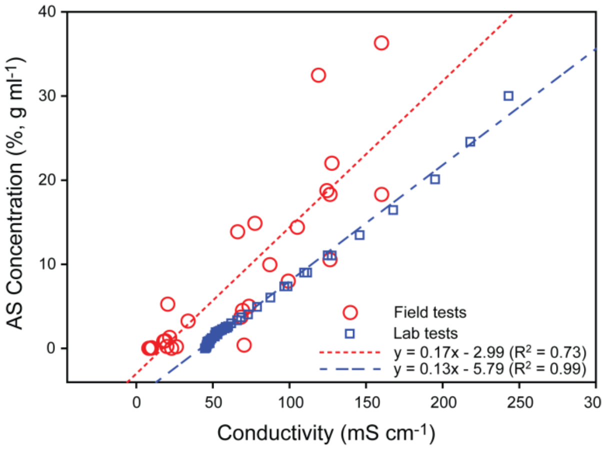


Figure 6 Correlation between ammonium sulfate concentration and effluent conductivity observed during scrubber operation at the field and lab.

### 3.3 Modeling AS production

The key factors that are identified to affect production of ammonium sulfate are airflow rate, inlet $NH_3$ concentration, scrubber efficiency, and duration of scrubber operation. The production rate of ammonium sulfate (AS)based on nitrogen balance of air stream passing through the scrubber is presented in Equation 3:

$$P_{AS} = 1.2 \times 10^{-4} * \beta * Q * C_{NH_3} * \eta * t \qquad (3)$$

where $P_{AS}$ is the production rate of ammonium sulfate (AS) in kg;$\beta$ is a coefficient that describes the discrepancy between the estimated AS production of the scrubber from air stream nitrogen balance and liquid side mass balance; $Q$ is the flow rate of air through the scrubber in $m^3$/hr; $C_{NH_3}$ is the inletair $NH_3$ concentration in $ppm_v$;$\eta$ is the scrubber efficiency in %; and $t$ is the duration of scrubber operation in days.

Production was expected to behave linearly with respect to each variable considering all other conditions remained constant, and thus each variable has the same sensitivity to the production. Meanwhile, within the variables affecting the production, scrubber efficiency inversely correlates with the natural log of inlet air $NH_3$ concentration between 10 $ppm_v$ and 400 $ppm_v$ (Hadlocon et al., 2014a).Inverse correlation was observed for the operation of the swine scrubber with inlet $NH_3$ concentrations ranging from 4to 65 $ppm_v$ (Hadlocon et al., 2014b). However, this correlation was not significant for higher ranges of inlet $NH_3$ concentrations, as observed in the operation of the poultry scrubber with inlet $NH_3$ concentration between 100 to 400 $ppm_v$(Hadlocon et al., 2014c).

Figure 7 shows the AS production curves for the scrubbers. The AS production rates estimated from air stream nitrogen balance for swine and poultry operations as represented by the slopes of the production curves were 1.53 kg/d (0.56 tonnes/yr) and 60.96 kg/d (22.25 tonnes/yr), respectively. Ammonium sulfate production for poultry scrubber operation can further increase to184.7 kg/d (67.4 tonnes/yr), if the air filtration system before the scrubber was not used.

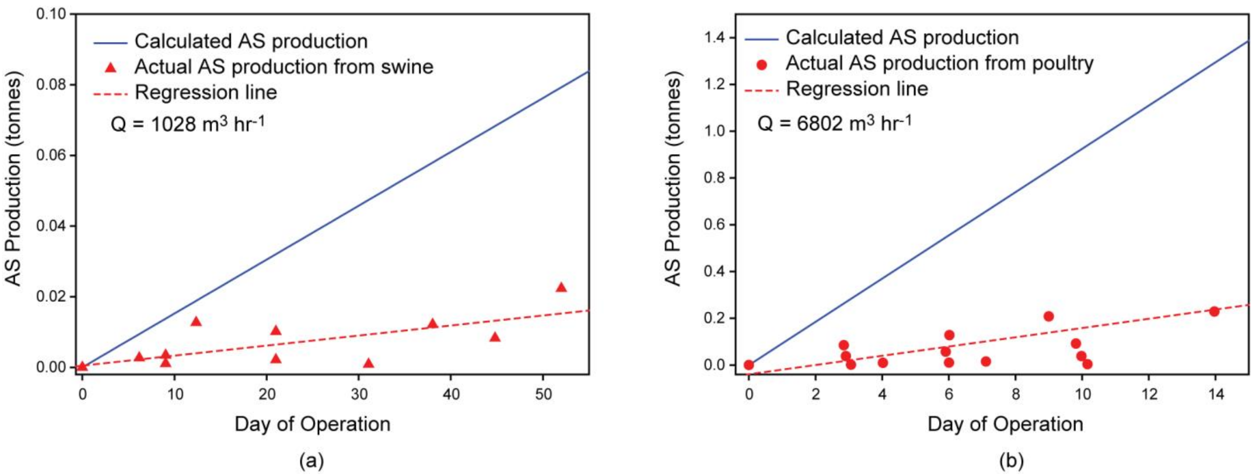
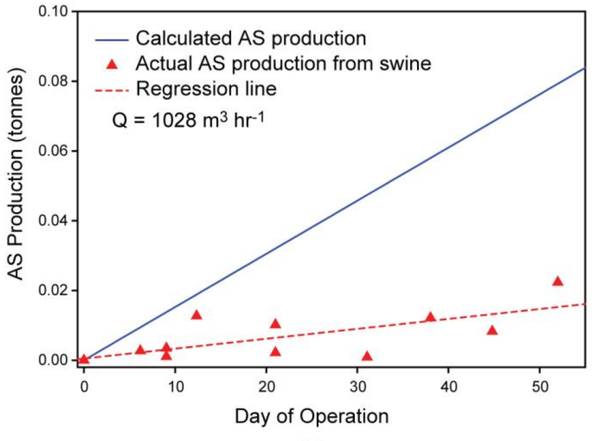


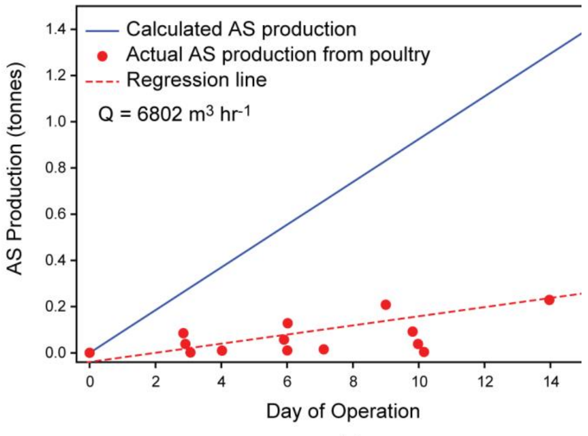
Figure 7 Calculated and actual AS production from (a) swine scrubber and (b) poultry scrubber

The actual AS productions obtained from the scrubber effluent analysis were plotted in Figure 7, which shows strong linearity for both the swine (R=0.73) and poultry operations (R=0.75). Regression analysis reveals that the actual AS production rates per scrubberat bothpoultry and swine facilities were only 0.28 kg/d (0.10 tonnes/yr) and 19.7 kg/d (7.2 tonnes/yr), respectively. The actual production rates for the entire facility were extrapolated assuming each of their pit fans has a scrubber installed. For the swine facility with 1,000 finishing pigs and 6 pit fans, the estimated production was 1.68 kg/d, while for the poultry manure composting facility with 12 exhaust fans receiving manure of 0.8 million birds, the total production rate was 236.4 kg/d (0.30 kg/d per 1000 laying hens).The calculated $\beta$ based on the actual AS production curves, initial airflow rate of scrubber, average inlet $NH_3$ concentration, and the average scrubber efficiency (as reported in Table 1),for operations of acid spray scrubbers at swine and poultry facilities were only 0.18 and 0.32, respectively. The $\beta$ values indicated significant difference between estimated AS production based on nitrogen balance analysis of air streams through the wet scrubber and the actual AS production of the scrubbers. These discrepancies were caused by errors from both the airstream nitrogen balance calculation and the liquid AS mass balance analysis. For the air stream nitrogen balance analysis, key factors including airflow rate, inlet ammonia concentration, and scrubber efficiency were all dynamically varying in animal facilities. In the case of the poultry scrubber operation, residential glass fiber air filters were used to reduce dust, causing the airflow rate to likely decrease over the test duration due to accumulated dust during the scrubber operation. Therefore, the actual airflow rate was much lesser than the initially measured airflow rate with clean filters. This is why the calculation using the initial airflow rate may have overestimated the AS production. For the liquid nitrogen balance analysis, the AS production may be underestimated due to liquid losses from scrubber leaks (caused by weld damages and pump seal breakage), air entrainment of droplets, and salt precipitation inside the scrubber that was not washed into the tank (Hadlocon et al., 2014b; Hadlocon et al., 2014c). A good dust control for the poultry scrubber is needed to maintain a relatively stable airflow rate. Improvements to reduce leak of the scrubbers and to realize long-term continuous operation are also necessary to further increase the $\beta$values of the scrubbers.

Production costs per kg AS produced of each scrubber were also estimated based on the preliminary economic analysis presented in the previous studies (Hadlocon et al., 2014b; Hadlocon et al., 2014c). Approximate fixed and operating costs of the scrubber operation at each facility were estimated based on the representative data obtained from the field at each season, and were annualized for each exhaust fan treated. For the swine scrubber operation, the production cost based on the capacities of the scrubber is \$5.74 per kg AS, while for poultry operation, it is about \$1.11per kg AS. The poultry scrubber operation is more economical and more profitable for AS production due to its higher $NH_3$ concentration and airflow rate capacity. The current market cost of fertilizer-grade AS could range from \$1.32 to \$3.85 per kg AS (AMSP, n.d.). There is still a need to further optimize the costs of scrubber materials and operation to make acid spray scrubbing a competitive method for AS production.If the environmental credit of this ammonia mitigation and fertilizer production process is considered, the process can be more economically competitive.



(a)



(b)

### 3.4 Potential utilization strategies

Results suggested that the scrubber effluent could be a good fertilizer for field crop production as it is very rich in N and is comparable with commercial ammonium sulfate fertilizers. Typical concentrations of $(NH_4)_2SO_4$in commercial liquid fertilizers can range from 32% to 54%, which may also require dilution before direct application on crops (Considine, 2005). Typical pH values of these fertilizers are between 5 and 7. Therefore, the low pH of the scrubber effluent remains an issue. One option to adjust the acidity of the solution is the addition of basic compounds such as lime. Another way is to allow the scrubber to operate without adding acid after the scrubbing solution has reached the desired AS concentration, and then stop the scrubber operation until pH rises within neutral range. Another utilization strategy for the effluent is to use it as a compost additive. Studies showed that AS helps reduce ammonia volatilization of compost. Spraying the AS effluent to the compost can also enhance the nitrogen value of the compost. Carey (1997) showed that 81% to 100% nitrogen would stay in the compost after treatment with ammonium sulfate with boost in N content. This option is promising, as it would not require future pH adjustments and compromise on scrubber efficiency during its terminal operation if pH control were stopped. Future work for the scrubber effluents as amenders for the compost has already been suggested (Elwell et al., 1998).

## 4. Conclusion

Acid spray wet scrubbers installed on the exhaust fans of animal facilities present an alternative method for nitrogen fertilizer production. This method has been field-tested and demonstrated at a commercial swine finishing and poultry manure composting facilities in the U.S.

Ammonium content in the effluent of the scrubbers was found to be promising for further utilization in agriculture. Stable operation of the swine scrubber generated about 568-L effluent with 9.0% to 18.7% (g/ml) of ammonium sulfate over 19-42 days of operation, while the poultry scrubber produced 1514-L effluent with 18.3% to 36.3% (g/ml) AS at a much shorter duration (10-17 days) due to higher inlet $NH_3$ concentration and high air flow rate from the poultry exhaust stream. Effluents with up to 36%(g/ml) AS did not show a significant effect on the ammonia absorption efficiency of the scrubber. The results showed that the acid spray scrubbers were capable of producing AS fertilizer that is comparable with commercial grade nitrogen fertilizer. Elemental analyses showed presence of trace amounts of nutrients in the effluent captured from exhaust air streams of animal facilities and confirmed that there was no other toxic substance in the scrubber effluents.

The AS production rates were also analyzed using mass balance analysis, which showed that the production rates for the swine and poultry scrubbers could be 1.53 kg/d and 60.96 kg/d, respectively. The actual production rates achieved were0.28 kg/d and 19.7 kg/d for swine and poultry scrubber, respectively. Improvements on the scrubber operation to control dust without significant airflow reduction, prevent leakages to reduce AS losses, and reduce possible losses of droplets through air entrainment, are needed to increase AS production yield and reduce production cost.

Possible utilization strategies of the scrubber effluents were also identified. When used as N fertilizer, further pH adjustments to make it suitable for field crop application are needed. The effluents can also be utilized as amenders for composts to minimize ammonia volatilization and increase their nutrient contents. There is still a need to conduct future research on the use of the actual effluents as fertilizer and compost additive to determine its effects on the crop yield, as well as on its influence on ammonia volatilization from manure compost buildings.

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