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Abstract

It is essential to mitigate gaseous emissions that result from poultry and livestock production to increase industry sustainability. Odorous volatile organic compounds (VOCs), ammonia (NH₃), hydrogen sulfide (H₂S), and greenhouse gases (GHGs) have detrimental effects on the quality of life in rural communities, the environment, and climate. This study's objective was to evaluate the photocatalytic UV treatment of gaseous emissions of odor, odorous VOCs, NH₃, and other gases (GHGs, O₃ – sometimes considered as by-products of UV treatment) from stored swine manure on a pilot-scale. The manure emissions were treated in fast-moving air using a mobile lab equipped with UV-A and UV-C lights and TiO₂-based photocatalyst. The treatment effectiveness depended on the UV dose and wavelength. Under UV-A (367 nm) photocatalysis, the percent reduction of targeted gases was up to i) 63% of odor, ii) 51%, 51%, 53%, 67%, and 32% of acetic acid, propanoic acid, butanoic acid, p-cresol, and indole, respectively, iii) 14% of nitrous oxide (N₂O), iv) 100% of O₃, and 26% generation of CO₂. Under UV-C (185+254 nm) photocatalysis, the percent reductions of target gases were up to i) 54% and 47% for p-cresol and indole, respectively, ii) 25% of N₂O, iii) 71% of CH₄, and 46% & 139% generation of CO₂ & O₃, respectively. The results proved that the UV technology was sufficiently effective in treating odorous gases, and the mobile lab was ready for farm-scale trials. The UV technology can be considered for the scaled-up treatment of emissions and air quality improvement inside livestock barns.

Keywords

Air pollution control, air quality, volatile organic compounds, odor, environmental technology, advanced oxidation, UV

Disciplines

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Pilot-scale evaluation of UV-A & UV-C photocatalytic treatment for mitigating odorous gas emissions from swine manure

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ABSTRACT. *It is essential to mitigate gaseous emissions that result from poultry and livestock production to increase industry sustainability. Odorous volatile organic compounds (VOCs), ammonia (NH₃), hydrogen sulfide (H₂S), and greenhouse gases (GHGs) have detrimental effects on the quality of life in rural communities, the environment, and climate. This study's objective was to evaluate the photocatalytic UV treatment of gaseous emissions of odor, odorous VOCs, NH₃, and other gases (GHGs, O₃ – sometimes considered as by-products of UV treatment) from stored swine manure on a pilot-scale. The manure emissions were treated in fast-moving air using a mobile lab equipped with UV-A and UV-C lights and TiO₂-based photocatalyst. The treatment effectiveness depended on the UV dose and wavelength. Under UV-A (367 nm) photocatalysis, the percent reduction of targeted gases was up to i) 63% of odor, ii) 51%, 51%, 53%, 67%, and 32% of acetic acid, propanoic acid, butanoic acid, p-cresol, and indole, respectively, iii) 14% of nitrous oxide (N₂O), iv) 100% of O₃, and 26% generation of CO₂. Under UV-C (185+254 nm) photocatalysis, the percent reductions of target gases were up to i) 54% and 47% for p-cresol and indole, respectively, ii) 25% of N₂O, iii) 71% of CH₄, and 46% & 139% generation of CO₂ & O₃, respectively. The results proved that the UV technology was sufficiently effective in treating odorous gases, and the mobile lab was ready for farm-scale trials. The UV technology can be considered for the scaled-up treatment of emissions and air quality improvement inside livestock barns.*

Keywords. *Air pollution control, air quality, volatile organic compounds, odor, environmental technology, advanced oxidation, UV.*

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Introductions

Poor indoor air quality and gaseous emissions are undesirable side effects of livestock and poultry production. Gaseous emissions of odor, odorous volatile organic compounds (VOCs), ammonia (NH₃), hydrogen sulfide (H₂S), and greenhouse gases (GHGs) have detrimental effects on the quality of life in rural communities, the environment, and climate. Proven mitigation technologies are needed to increase the sustainability of animal agriculture. The farm-scale readiness and the effectiveness of technologies for mitigation of gaseous emissions from livestock agriculture are summarized by Maurer et al. (2016). The user-friendly description of technologies and the scientific literature database is provided by the Iowa State University Extension and Outreach website.

Photocatalysis with UV (ultraviolet) light has received considerable attention for special applications in indoor air quality. However, the research of UV photocatalysis in livestock agriculture applications is still limited. Costa et al. (2012) and Guarino et al. (2008) pioneered UV-A photocatalysis at a swine nursery and reported mitigation of NH₃, GHGs, particulate matter (PM), and increased feed conversion efficiency. However, the previous research's technical design information, such as light dose and photocatalyst coating thickness required for application to actual farms, was not provided. Our team has been motivated by these early examples of farm-scale applications in Europe to conduct lab-to-farm-scale research to scale up and adapt UV photocatalysis to the swine farming systems prevailing in the American swine industry.

Several lessons were learned from the lab-scale to the pilot-scale progression of research. Zhu et al. (2017) showed that a TiO₂ based photocatalytic coating (PureTi, Cincinnati, OH, USA) is sufficient to effectively mitigate odorous VOCs. Research showing the reduction of NH₃ and odorous VOCs with UV-C followed (Kozziel et al., 2008; Rockafellow et al., 2012; Yang et al., 2020;). Recently, the application of UV-A photocatalysis for NH₃, odorous VOCs, ozone, and nitrous oxide (N₂O) was shown (Lee et al., 2020a; Lee et al., 2020b). Testing UV-A photocatalysis (a safer bandwidth for direct human and animal exposure) showed a mitigation effect on a pilot-scale in the actual livestock farm environment (Maurer & Kozziel, 2019; Lee et al., 2020a; Lee et al., 2020b;).

Thus, earlier tests show practical percent reduction efficiencies for several targeted odorous air pollutants using marketed spray-on coatings for indoor building materials. Still, practical research questions must be addressed before the UV-A (or UV-C) technology can be adopted for farm-scale application to barn interiors to improve air quality inside livestock barns. Also, there is an interest in scaling up the UV treatment to mitigate emissions from the barn exhaust air. There is also an interest in UV-C applications to mitigate the risk of airborne pathogens from the ambient air, feed, supplies, personnel threatening farm biosecurity, and using UV to lower the pathogen load inside barns (Li et al., 2021;).

This research aimed to scale up TiO₂-based photocatalysis treatment with UV-A and UV-C light to pilot-scale conditions. Specifically, the objective was to evaluate the percent reduction of gaseous emissions generated from swine manure, where the realistic mix of gases and aerosols was treated at fast-moving air and airflows consistent with those on production-scale farms. This study used a mobile UV laboratory designed and commissioned for testing with large (~1 m³/s) airflows (Lee et al., 2021b;). Results from this study are needed to inform the experimental design for future on-farm research with UV-A and UV-C.

Materials and Methods

The mobile laboratory (7.2 × 2.4 × 2.4 m) designed and verified in the previous study (Lee et al., 2021b) was used in this study. The mobile laboratory consisted of 12 chambers (7.2 × 0.9 × 2.4 m), and each chamber (0.5 × 0.9 × 2.4 m) was divided into vertical baffles. Chambers #11 and #12 were connected without a vertical baffle. Each chamber was equipped with 11 panels coated with TiO₂ (nanostructured TiO₂ anatase at 10 µg/cm² from PureTi, Cincinnati, OH, USA) on all sides. Two fans (I-Fan Type 40, Fancom, Panningen, The Netherlands) were installed on the mobile laboratory to control the airflow inside. The air velocity was measured with the anemometer fan (ATM, Fancom, Panningen, The Netherlands) installed in chamber #10, and the internal airflow can be controlled in real-time using the fan monitoring system (Lumina 20/21, Fancom, Panningen, The Netherlands) by controlling the two fan and the anemometer fan.

Generation of odorous gas emissions from swine manure

A plastic drum (55 gal, ~200 L) filled with 35-40 gal of swine manure was used to generate a realistic mixture of odorous gases and aerosols and investigate UV photocatalysis performance (illustrated in Lee et al., 2021a; Figure 1). Compressed air was continuously supplied to the bottom of the manure, and the headspace gas was blended with ambient air. A filtration unit prevented the inflow of flies and dust into the UV mobile lab. Detailed information about the mobile laboratory and filter house has been reported in the previous study (Lee et al., 2021b).

Tested UV sources

In this study, the mitigation of target gases was investigated using four different light sources (UV-A: 367 nm and UV-C: 254 nm, 222 nm, 185+254 nm, illustrated in Lee et al., 2021a; Figure A2). Two different low-pressure mercury sources were used, both of which emit strongly at 254 nm, but one additionally contains a small 185 nm component because the bulb is

made from special materials that allow transmission of that line. The emission spectrum of low-pressure mercury lamps is well known, and these sources both also contained small emissions at 365 nm and other wavelengths common to all of these bulbs. Nonetheless, we refer to these as 254 nm or (185 + 254) nm light sources. An excimer source emitting at 222 nm was the third source; these three sources constitute variations on wavelengths between 222 nm and 365 nm. The fourth source was an LED with emission centered at 367 nm, quite near the 365 nm range that mercury lamps commonly were used for, but without many of the disadvantages of a mercury-based lamp. This is considered within the UV-A region.

Each chamber inside the mobile laboratory was equipped with 5 UV-A LED lamps (T8 LED, Eildon Technology, Shenzhen, China). An additional 100 UV-A lamps (effectively adding 20 times the light intensity, illustrated in Lee et al., 2021a;) were installed on a removable rack in each of the two chambers (#2-#3) to investigate the reduction of targeted gases according to the UV dose (illustrated in Lee et al., 2021a; Figure 2). Detailed information on UV-A lamps used in this study was reported previously (Lee et al., 2021b).

All UV-C sources were tested inside chamber #2 while all the UV-A lights in other chambers were turned off. For UV-C (254 nm and 185+254 nm, American Ultraviolet Co, Lebanon, IN, USA), 4 lamps of each different wavelength were installed on the door in one chamber (#2). In the case of the 222 nm excimer UV-C (Ushio America Inc., Cypress, CA, USA), one lamp (Care222 Series) and power supply were installed on the door in chamber #2 (illustrated in Lee et al., 2021a; Figure A2). The effects of UV wavelength were measured locally in chamber #2 for all lamp types. The targeted gas concentrations in the untreated gas (control) were measured in the #1 chamber's sampling port. The treated gas concentration after the UV treatment was measured in the #3 chamber's sampling port (illustrated in Lee et al., 2021a; Figures 1 and 2).

The light intensity of different UV wavelength lamps

The light intensity is needed to estimate the UV irradiation (and therefore, the dose when integrated over time). The light intensity was measured by ILT-1700 radiometer (International Light Technologies, Peabody, MA, USA) with wavelength-specific sensors and filters. The UV-C 254 nm, 222 nm, 185 nm, and UV-A 365 nm was measured by the SED240 sensor (w/ NS254 filter; 254 ± 5 nm); SED240 sensor (w/ NS220 filter, 220 ± 5 nm); SED185 sensor (w/ NS185 filter, 185 ± 5 nm); and SED033 sensor (w/ NS365 filter, 365 ± 5 nm), respectively. The 222 nm sensor only imperfectly excludes light from its intended window, and non-zero artifactual measurements were seen with the two Hg sources. All UV lamps were turned on for 5 min before each measurement or experimental run to ensure stable and consistent UV irradiation. For techno-economic analysis, the electric power consumption was measured using a wattage meter (P3, Lexington, NY, USA). The summary of measured light intensity inside the mobile lab under different UV wavelengths and doses is shown in Lee et al., (2021a).

Measurement of odor

Gas samples for odor analyses were collected from the inlet and outlet gas sampling ports inside the UV mobile lab into 10 L Tedlar bags using a Vac-U-Chamber and sampling pump (both from SKC Inc., Eighty-Four, PA, USA). Tedlar bags were pre-cleaned by flushing with clean air three times before use. Gas samples were analyzed for odor using a dynamic triangular forced-choice olfactometer (St. Croix Sensory Inc., Stillwater, MN, USA). Four trained panelists at two repetitions each were used to analyze each sample, presented from low to increasingly lower dilutions to the point of consistent odor detection.

Measurement of odorous volatile organic compounds

Odorous VOCs, such as sulfur-containing VOCs, volatile fatty acids (VFAs), and phenolic compounds, are significant contributors to livestock odor (Lo et al., 2008;). VOC analysis was conducted in the same way as described in detail in the previous study (Banik et al., 2020; Chen et al., 2020;). Briefly, VOC samples were collected in 1 L gas sampling glass bulbs. An internal standard (hexane) was used to minimize variability in sampling and sample preparation. A 2 cm DVB/Carboxen/PDMS solid-phase microextraction (SPME) fiber (Supelco, Bellefonte, PA, USA) was used to extract VOCs from the glass bulbs for 50 min, then analyzed with a GC-MS within 12 h of sample collection. The NIST mass spectral library (with at least 80% spectral match) was used to confirm the compounds' identity. A set of 15 standards for targeted odorous VOC were used (acetic acid, propionic acid, isobutyric acid, butyric acid, isovaleric acid, valeric acid, hexanoic acid, dimethyl disulfide, diethyl disulfide, dimethyl trisulfide, guaiacol, phenol, p-cresol, 4-ethyl phenol, indole, and skatole) and calibrated to verify the GC retention time and MS spectral signal.

Measurement of ozone concentrations

Ozone is generated during UV-C irradiation of air, and thus, it was a targeted gas. On the other hand, the generated O₃ can react and mitigate odorous VOCs. In this research, the O₃ detector was connected to the monitoring system (Series 500 monitor, Aeroqual, New Zealand) and installed at the gas sampling ports when in use. The detector was factory-calibrated (Gas Sensing, IA, USA) and certified before use. The detection range was 0 to 50 ppb.

Measurement of greenhouse gas concentrations

UV treatment of odorous VOCs and NH₃ can result in the generation of GHGs that should be tracked. Methane (CH₄), carbon dioxide (CO₂), and nitrous oxide (N₂O) were measured. GHGs samples were collected using syringes and 5.9 mL Exetainer vials (Labco Limited, UK) and were analyzed for concentrations on a GC equipped with FID and ECD detectors (SRI Instruments, Torrance, CA, USA). Samples were analyzed on the day of collection. Standard calibrations were constructed daily using 10.3 ppm and 20.5 ppm CH₄, 1,005 ppm and 4,010 ppm CO₂, and 0.101 ppm and 1.01 ppm N₂O. Pure helium was used to calibrate the baseline of 0 ppm (Air Liquide America, Plumsteadville, PA, USA).

Measurement of ammonia and hydrogen sulfide concentrations

Ammonia (NH₃) is a major contributor to air pollution from livestock operations. Hydrogen sulfide (H₂S) is a toxic air pollutant and a significant contributor to odor. NH₃ and H₂S concentrations were measured with a real-time analyzer (OMS-300, Smart Control & Sensing, Daejeon, Republic of Korea) calibrated with high precision standard gases (5-point dilution, R²=0.99). The analyzer was equipped with NH₃/CR-200 and H₂S/C-50 electrochemical gas sensors (Membrapor, Wallisellen, Switzerland), NH₃/CR-200 (0 to 100 ppm), and H₂S/C-50 (0 to 50 ppm), respectively.

Data measurement and analysis

Gas samples were collected after 30 min of equilibration time under each treatment condition. The overall mean % reduction (mitigation) for each measured gas was estimated using:

$$\% \text{ Reduction} = \frac{E_{con} - E_{Treat}}{E_{con}} \times 100 \quad (1)$$

where

E_{Con} and E_{Treat} = the mean measured concentrations in control and treated air, respectively

Emission rates were calculated as a product of measured gas concentrations and the total airflow rate through the wind tunnel, adjusted for standard conditions and dry air using collected environmental data. The overall mean mitigation of each measured gas emission was estimated using:

$$\text{Mitigation of emission} = \left(C_{con} \times V \times \frac{273.15 \times MW}{(K_{Con}) \times 2.24 \times 10^4} - C_{Treat} \times V \times \frac{273.15 \times MW}{(K_{Treat}) \times 2.24 \times 10^4} \right) \quad (2)$$

Where:

Mitigation of emission (g min⁻¹) = the mitigation of gas emission

C_{Con} and C_{Treat} = the mean measured concentrations in control and treated air (mL m⁻³), respectively

V = the ventilation rate (m³ min⁻¹)

MW = the molecular weight of target gas (g mol⁻¹)

K_{Con} and K_{Treat} = the temperature in control and treated air (K), respectively

2.24 x 10⁴ = an ideal gas conversion factor for liters to moles at 273.15 K.

UV dose (Eq. 3) was estimated using measured light intensity (I) at a specific UV wavelength (mW·cm⁻²) and treatment time (ts, s).

$$\text{UV dose} = I \times ts \quad (3)$$

Statistical analysis

The overall mean percent reduction for each measured targeted gas was estimated using: The R studio (version 3.6.2) was used to analyze the target standard gases' mitigation under UV photocatalysis treatment. The UV dose and treatment time parameters between control concentration and treatment concentration were statistically analyzed using one-way ANOVA. The statistical difference was confirmed by obtaining the p-value through the Tukey test. A significant difference was defined for a p-value <0.05 in this study.

Results

1. Mitigation of targeted gases as a function of UV-A dose controlled by light intensity and airflow rate

1.1 Odor – effects of UV-A dose

The UV-A photocatalysis showed a significant percent odor reduction (32-63%). The UV dose of 2.5 mJ/cm² was required for statistically significant odor reduction (illustrated in Lee et al., 2021a; Table 1). As the UV dose was increased, the odor reduction increased up to 63%.

1.2 Volatile organic compounds – effects of UV-A dose

UV-A photocatalysis significantly mitigated selected targeted odorous VOCs while also generating a small subset of other VOCs. This is an important observation as the complex and compound-specific photocatalytic reactions can affect the overall percent reduction of odor. UV-A dose ≥ 2.5 mJ/cm² was required to mitigate phenolic compounds (illustrated in Lee et al., 2021a; Table 2), similarly to the findings for odor where the same UV dose resulted in significant mitigation (Table 1). As the UV dose increased up to ~ 3.9 mJ/cm², the percent reduction of VOCs and the number of mitigated (targeted) VOCs increased. The highest percent reductions were measured for acetic acid (49%), butanoic acid (53%), p-cresol (67%), and indole (32%). The highest dose (5.8 mJ/cm²) did not improve the mitigation effect, suggesting that there is merit to optimizing the UV dose, especially from the techno-economic standpoint.

1.3 Ozone – effects of UV-A dose

Compared with a baseline (ambient air) amount of O₃ detected without UV irradiation, the concentration of O₃ was effectively mitigated (up to 100%) by UV-A irradiation. This observation was consistent with our earlier UV-A research in lab-scale and pilot-scale (poultry farm) conditions (Lee et al., 2020a; Lee et al., 2020b;). Therefore, the treatment of the lowest UV dose (1.3 mJ·cm⁻²) is the most economical condition if O₃ is the targeted gas. It is also important to mention that the mean O₃ concentration in the UV mobile lab outlet was 4.7 ppb. This concentration is relatively low and likely of low concern for scaling up to farm environments, where abundant VOCs are present to react with O₃ and further reduce the risk of its release to the atmosphere outside the barn.

1.4 Greenhouse gases – effects of UV-A dose

The N₂O concentrations were significantly reduced (by 4 to 14%) with UV-A photocatalysis for 2.5 mJ/cm² or higher doses (illustrated in Lee et al., 2021a; Table 4). However, there was no statistically significant change in CH₄ concentrations (illustrated in Lee et al., 2021a; Table S8), and there was a significant generation of CO₂ (up to -26%) (illustrated in Lee et al., 2021a; Table S9) that increased with the UV dose.

1.5 Ammonia and hydrogen sulfide – effects of UV-A dose

Significant percent reduction of NH₃ concentrations was measured only for the maximum UV-A dose (5.8 mJ/cm²). The treatment efficiency was low (6 %), similar to the previous reports (Lee et al., 2020a; Lee et al., 2020b;). The mean NH₃ concentration in control was 5.4 ppm. No steady concentration of H₂S was measured in control (likely due to the limited supply of it in manure). The H₂S was typically detectable at the start of the experiment, but its concentration in control was rapidly diminishing, preventing reproducible measurements after UV-A treatment. This limitation will be addressed in farm-scale trials, where H₂S in barn air or barn exhaust is continuously present, the mitigation of H₂S can be objectively tested.

2. Comparison of the mitigation of targeted gases as a function of UV wavelength

The comparison of UV-A and UV-C photocatalysis treatment was conducted in only one chamber (#2) due to the limited number of available UV-C lamps that are more costly than UV-A. The results are summarized below. Testing conditions were the same for all lamps to enable a fair side-by-side comparison.

2.1. Odor – effects of UV wavelength

The short UV-C wavelength (185 + 254 nm) resulted in a 44% reduction of overall detected odor. This was a remarkable mitigation effect, considering that the UV dose was the lowest among all tested (illustrated in Lee et al., 2021a; Table 6). However, odor reduction was not significant for all treatments ($0.09 < p\text{-value} < 0.94$). This was likely due to the variability of control used for just one treatment chamber tested (illustrated in Lee et al., 2021a; Table 6). Odor measurements via dilution olfactometry and human panelists are inherently more variable than chemical analyses. This limitation could be addressed by refurbishing the entire UV mobile laboratory with one type of lamp, effectively allowing a more extensive range of doses to be tested (e.g., lower variability reported for UV treatment using an entire mobile lab with 12 chambers facilitating treatment, illustrated in Lee et al., 2021a; Table 1).

2.2. Volatile organic compounds – effects of UV wavelength

The phenolic compounds of p-cresol and indole were effectively treated with UV-C (185+254 nm) with a statistically significant percent reduction at 47 and 54%, respectively (illustrated in Lee et al., 2021a; Table 7). p-Cresol and indole are often referred to as the 'signature' barnyard odors and potent odorants; thus, their mitigation is consistent with the results for overall odor reduction (illustrated in Lee et al., 2021a; Table 6). The UV-C (185+254 nm) dose was the lowest tested, yet the percent reductions for other targeted VOCs were notable and ranged from 10 to 59%. The 185+254 nm light source is essentially identical to the 254 nm light source, save that the 'glass' of the lamp itself additionally transmits a small amount

of very high energy 185 nm photons. The additional 185 nm irradiation (when part of 185 + 254 nm treatment) results in effective reduction of targeted VOCs. The UV-C (254 nm and 222 nm) sources also effectively mitigated much targeted VOCs (from - 15 to 70%), although there is no significant statistical mitigation. The use of longer-wavelength UV-A (367 nm) and the highest dose resulted in a statistically significant reduction for acetic acid (57%) and butanoic acid (33%).

2.3. Ozone – effects of UV wavelength

O₃ was reduced at all wavelengths except for 185+254 nm. Specifically, complete mitigation (below detection limits) was measured for 222 nm and 254 nm treatments. The percent reduction increased from 30 to 97% as the UV dose increased for the 367 nm wavelength. O₃ increased by ~140% (illustrated in Lee et al., 2021a; Table 8) for the 185+254 nm treatment. This is due to the direct photolysis of O₂ in the air, which leads to O₃ formation.

2.4. Greenhouse gases – effects of UV wavelength

Significant mitigation was measured for CH₄, with the (185+254) nm lamps. However, other wavelength lamps did not show statistically significant reduction (illustrated in Lee et al., 2021a; Table 9). CO₂ concentrations increased for all UV wavelengths tested (illustrated in Lee et al., 2021a; Table S10) and were statistically significant for 185+254 nm and 367 nm (high UV dose). N₂O was mitigated at statistically significant levels (from 8 to 25%) for all treatments except for the low 367 nm dose (illustrated in Lee et al., 2021a; Table 10). The highest percent reduction for CH₄ and N₂O resulted from the 185+254 nm treatment.

2.5. Ammonia and hydrogen sulfide – effects of UV wavelength

There was no statistically significant reduction for all UV wavelengths tested, and the percent reduction ranged from 0.3 to 2.1% (illustrated in Lee et al., 2021a; Table 11). The average concentration of the control group was 3.1 ppm (illustrated in Lee et al., 2021a; Table 11). H₂S concentrations in control were not stable enough to warrant reporting the effect.

Discussion

UV photocatalysis can be considered a potential technology to reduce odorous gases and improve air quality. This research provides mitigation data for a more extensive set of odorants and air pollutants compared with the state-of-the-art. UV-A photocatalysis reduced several of the targeted odorous gases (illustrated in Lee et al., 2021a; Table 12) with statistical significance. The reproducibility of mitigation with UV-A photocatalysis warrants further scaling up into larger volumetric flowrates common for farm applications.

Caution needs to be exercised when extrapolating pilot-scale data. However, several major recommendations can be made. The UV-A treatment does not appear to be effective for farm-scale mitigation of NH₃, considering that the mitigation effect was rather small (illustrated in Lee et al., 2021a; Tables 5 and 11). Thus, effective reduction of kg/day quantities of NH₃ from typical swine farms with UV-A appears to be too costly.

On the other hand, mitigation of several targeted air pollutants is worth considering. For example, mitigation of N₂O (illustrated in Lee et al., 2021a; Tables 4 and 10) might be further exploited for farm income generation that uses subsidies and programs focused on reducing GHGs emissions and mitigating climate change. Direct emissions of O₃ from farms have not been a concern, as opposed to the secondary pollutant generation of O₃ as a by-product of emitted VOCs and their atmospheric chemistry. Thus, the incentivization and credit taking for the at-source mitigation of O₃ might be considered (Table 3 and 8). Finally, the significant reduction of odor and odorous VOCs is encouraging at this scale (illustrated in Lee et al., 2021a; Tables 1, 2, 6, and 7). Of course, planned farm-scale trials can provide a more realistic techno-economic assessment of UV-A cost. Farm-scale trials with the UV-A photocatalysis installed inside barns to mitigate indoor air quality and the pathogen load are warranted.

The effects of UV wavelength were only tested in one chamber inside the UV mobile lab due to increasing UV-C dose limitation. Thus, the comparison is somewhat limited (illustrated in Lee et al., 2021a; Table 14). Therefore, the results show the UV-C's future potential that still needs to be tested on a larger scale. The UV-C can efficiently reduce odorous VOCs with a lower dose (compared to UV-A). One caveat to UV-C use is risks associated with direct skin and eye tissue exposure and O₃ generation.

Conclusion

This study evaluated the photocatalytic UV-A and UV-C treatment of gaseous emissions of odor, odorous VOCs, NH₃, and other gases (GHGs, O₃) from stored swine manure on a pilot-scale. The treatment effectiveness depended on the UV dose and wavelength. Under UV-A (367 nm) photocatalysis, the percent reduction of targeted gases was up to:

- 63% of odor,
- 51%, 51%, 53%, 67%, and 32% of acetic acid, propanoic acid, butanoic acid, p-cresol, and indole, respectively,

- 14% of nitrous oxide (N₂O),
- 100% of O₃, 6% of NH₃, and
- 26% generation of CO₂.

Under UV-C (185+254 nm) photocatalysis, the percent reduction of target gases was up to:

- 54% and 47% for *p*-cresol and indole, respectively,
- 25% of N₂O,
- 71% of CH₄, and
- 46% & 139% generation of CO₂ & O₃, respectively.

The UV-C (222 nm) photocatalysis showed a reduction of 8% for N₂O, 100% for O₃. Lastly, UV-C (254 nm) photocatalysis showed a reduction of 14% for N₂O, 100% for O₃. The results proved that the UV technology was sufficiently effective in treating odorous gases, and the mobile lab was ready for farm-scale trials. The UV technology can be considered for the scaled-up treatment of emissions and air quality improvement inside livestock barns.

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