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Design, testing, and commissioning of mobile laboratory for mitigation of gaseous emission from livestock barns with photocatalysis

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Abstract

Livestock production systems generate nuisance odor and gaseous emissions affecting local communities and regional air quality. Also, there are concerns about the occupational health and safety of farm workers. Proven mitigation technologies that are consistent with the socio-economic challenges of animal farming are needed. We have been scaling up the photocatalytic treatment of emissions from lab-scale, aiming at farm-scale readiness. In this paper, we present the design, testing, and commissioning of a mobile laboratory for on-farm research and demonstration of performance in simulated farm conditions before testing to the farm. The mobile lab is capable of treating up to 1.2 m3·s-1 of air with TiO2-based photocatalysis and adjustable UV-A dose based on LED lamps. We summarize the main technical requirements, constraints, approach, and performance metrics for the mobile laboratory, such as the effectiveness (measured as the percent reduction) and cost of photocatalytic treatment of air. The commissioning of all systems with standard gases resulted in ~9% and 34% reduction of NH3 and butan-1-ol, respectively. We demonstrated that as the percent reduction of standard gases increased with increased light intensity and treatment time. These results show that the mobile laboratory was ready for on-farm deployment and evaluating the effectiveness of UV treatment.

Keywords

Air pollution control, air quality, volatile organic compounds, odor, environmental technology, advanced oxidation, UV-A; titanium dioxide

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Environmental Chemistry | Environmental Health

Comments

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Design, testing, and commissioning of mobile laboratory for mitigation of gaseous emission from livestock barns with photocatalysis

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ABSTRACT. *Livestock production systems generate nuisance odor and gaseous emissions affecting local communities and regional air quality. Also, there are concerns about the occupational health and safety of farm workers. Proven mitigation technologies that are consistent with the socio-economic challenges of animal farming are needed. We have been scaling up the photocatalytic treatment of emissions from lab-scale, aiming at farm-scale readiness. In this paper, we present the design, testing, and commissioning of a mobile laboratory for on-farm research and demonstration of performance in simulated farm conditions before testing to the farm. The mobile lab is capable of treating up to 1.2* $m^3 \cdot s^{-1}$ *of air with* TiO_2*-based photocatalysis and adjustable UV-A dose based on LED lamps. We summarize the main technical requirements, constraints, approach, and performance metrics for the mobile laboratory, such as the effectiveness (measured as the percent reduction) and cost of photocatalytic treatment of air. The commissioning of all systems with standard gases resulted in ~9% and 34% reduction of* NH_3 *and butan-1-ol, respectively. We demonstrated that as the percent reduction of standard gases increased with increased light intensity and treatment time. These results show that the mobile laboratory was ready for on-farm deployment and evaluating the effectiveness of UV treatment.*

Keywords. *Air pollution control, air quality, volatile organic compounds, odor, environmental technology, advanced oxidation, UV-A; titanium dioxide.*

Introductions

Over the past few decades, livestock and poultry farmers have adopted new technology and have scaled up farming operations to meet society's demand for high-quality meats, milk, eggs, and by-products. Large confined animal feeding operations (CAFOs) are common in many parts of the world. This has generated profits and jobs, but the environmental problems associated with the local air quality have been exacerbated. These unwanted side effects of animal production require sustainable solutions for the benefit of workers, rural communities, and the industry.

The U.S. National Air Emissions Monitoring Study (NAEMS) developed an accurate baseline emission database for CAFO regulation by the US EPA through the notification provisions of the Emergency Planning and Community Right-to-Know Act (EPCRA) and the Clean Air Act (CAA) (Cai et al., 2015; Heber et al., 2009). NAEMS and the companion projects focused on monitoring emissions of odor, odorous VOCs, ammonia (NH_3), hydrogen sulfide (H_2S), carbon dioxide (CO_2), methane (CH_4), the total suspended particulates (TSP), PM10, and PM2.5 in the egg, broiler, dairy, and swine production industries (Akdeniz et al., 2012a; Akdeniz et al., 2012b; Bereznicki et al., 2012; Cai et al., 2015; Heber et al., 2009). While the NAEMS can be used as a standard and a source of the pollutants emitted from farms, there is still a need to develop and test mitigation technologies that are consistent with the socio-economic reality of CAFOs. Mitigation technologies for gaseous emissions from livestock operations could be classified amongst approximately 12 approaches, including facility barriers, biofilters, chimneys, diet manipulation, electrostatic precipitation, landscaping, oil sprinkling, pit ventilation, scrubbers, siting, urine (or feces) segregation, and UV light (Iowa State University Extension and Outreach. Summarising the air management practices assessment tool in animal housing). The overview of each mitigation technology and citations to research papers is summarized elsewhere (Maurer et al., 2016).

Farm-scale performance data are a prerequisite for the adoption of proposed new technology. Farmers need proven technologies before agreeing on farm-scale trials. Well-intentioned, laboratory-scale experimentation cannot fully duplicate the on-farm variability. Maurer et al. (2016) summarized the current state of adoption of technologies for mitigation of gaseous emissions from livestock agriculture. Only ~25% of mitigation technologies developed and tested in lab-scale have been tested in real-farm conditions. We have been scaling up the photocatalytic treatment of emissions from the lab- to pilot-scales, aiming at farm-scale readiness (Koziel et al., 2008; Lee et al., 2020a; Lee et al., 2020b; Maurer & Koziel, 2019; Rockafellow et al., 2012; Yang et al., 2020; Yang et al., 2015; Zhu et al., 2017;). Several other research teams have also been testing UV photocatalytic technology (Cost et al., 2012; Guarino et al., 2008; Liu et al., 2015; Yao & Feiberg, 2015) for the mitigation of gaseous emissions from livestock operations.

UV light treatment is a promising technology for mitigating gaseous pollutants. The use of either shorter UV wavelengths or a photocatalyst improves the mitigation effects (Lee et al., 2020a; Rockafellow et al., 2012; Yang et al., 2020;). In addition, catalytic coating type, coating dose, UV dose, relative humidity, temperature, and dust accumulation (on photocatalyst) are important variables to consider and optimize for improved reduction of targeted odorous gases (Lee et al., 2020a; Zhu et al., 2017;). The photocatalytic treatment has been found to show a significant reduction in odorous VOCs even after short effective treatment times that are consistent with fast-moving ventilation air on farms(Koziel et al., 2008; Yang et al., 2020;). Previous studies have reported the varying effect of reducing NH_3, H_2S, greenhouse gases, VOCs, odor, and PM with UV in livestock farm conditions (Costa et al., 2012; Guarino et al., 2008; Koziel et al., 2008; Lee et al., 2020a; Lee et al., 2020b; Maurer & Koziel, 2019; Rockafellow et al., 2012; Yang et al., 2020).

Only a selected few studies reported on testing UV technology on a pilot scale (Lee et al., 2020b; Maurer & Koziel, 2019; Yang et al., 2020;) or farm-scale (Costa et al., 2012; Guarino et al., 2008;). For that reason, there is a lack of information on UV doses and the cost to reduce odorous gases in farm-scale conditions. Also, depending on the wavelengths of UV light, direct exposure to the light or its by-products (e.g., ozone) generated by shorter wavelength UV (e.g., 254 nm) can be risky to workers and livestock. Our previous research showed that the intrinsically safer UV-A (365 nm) could be effective in treating NH_3, N_2O, ozone, selected VOCs, and odor on lab- and pilot-scales (Lee et al., 2020a; Lee et al., 2020b; Maurer & Koziel, 2019;).

Therefore, we hypothesize that the UV-A-based photocatalysis can be effective in reducing selected gaseous emissions at a much larger scale. A UV-A mobile lab is a research tool that could be used to perform on-site trials at different farms and industrial emissions sources to demonstrate UV-A performance at realistic conditions. The farmers and industry appreciate these types of trials that do not disrupt current operations while providing necessary decision-making data. This was the motivation behind the design of a self-contained mobile laboratory that can directly sample the gases from a livestock farm and carry out the evaluation of photocatalysis UV treatment and cost prior to the next logical step, i.e., scaling up and installation of UV treatment on a farm or other emissions source.

The objective of this research was to design and test of mobile laboratory for mitigation of gaseous emission from livestock barns with UV-A photocatalysis. To our knowledge, this is the first study to evaluate the effect of UV-A photocatalysis treatment under conditions similar to a livestock farm using a mobile laboratory of this type. We summarize the main technical requirements, constraints, approach, and performance metrics for the mobile laboratory, such as the effectiveness (measured as the percent reduction) and cost of photocatalytic treatment of air. We provide the mitigation effect for two representative odorous gases (NH_3 and butan-1-ol) with the mobile laboratory.

Materials and Methods

Requirements for testing UV photocatalysis at the mobile laboratory

The mobile laboratory (7.2 m × 2.4 m × 2.4 m exterior dimensions) was designed to evaluate the effectiveness of UV photocatalysis by directly connecting to the exhaust gases emitted from the farm (illustrated in Lee et al., 2021; Figure 1). The technical requirements and constraints for the mobile laboratory are summarized in Table 1 (Lee et al., 2021;). It explains the approach, the performance metric, and the location of the detailed description in the manuscript that addresses each of the five main requirements and constraints. In summary, we have implemented 1) the construction of treatment chambers capable of irradiating UV light and collecting real-time gas samples, 2) control of the UV dose, 3) control of the airflow, 4) control of the photocatalyst dose, and 5) control of airborne particulate matter.

Light intensity measurement

Light intensity was measured (illustrated in Lee et al., 2021; Figure A.3) with an ILT-1700 radiometer (International Light Technologies, Peabody, MA, USA) equipped with an NS365 filter and SED033 detector (International Light Technologies, Peabody, MA, USA). Prior to use, the radiometer and sensor were sent to the manufacturer company (International Light Technologies, Peabody, MA, USA) for factory calibration. For economic analysis, the electric power consumption was measured using a wattage meter (P3, Lexington, NY, USA).

Measurement of standard gases concentration (NH3 and butan-1-ol)

Two odorous gases were used for testing and commissioning. The butan-1-ol (a representative standard gas for VOCs and a mild odorant) and NH_3 concentrations were measured in order to evaluate the percent reduction by UV photocatalysis treatment (illustrated in Lee et al., 2021; Figure 2). The calibrations for both standard gases were at $R^2 > 0.99$.

For NH^3, standard gas and dry air were adjusted using a mass flow controller (FMA5400A/5500A Series, OMEGA, Norwalk, USA) to make five diluted gas samples generally within the range of the target gas to be measured. In the case of NH3, diluted samples were collected in a Tedlar bag, and the concentration was measured using the gas monitoring system (OMS-300, Smart Control & Sensing Inc., Daejeon, Rep. of Korea) equipped with electrochemical gas sensors of Membrapor Co. (Wallisellen, Switzerland). The calibration curve is drawn using the obtained voltage from the sensor and the known concentration of the diluted sample (illustrated in Lee et al., 2021; Figure 3).

Air samples for butan-1-ol measurements were collected using 1 L glass gas sampling bulbs (Supelco, Bellefonte, PA, USA). Air samples were taken using a portable vacuum sampling pump (Leland Legacy; SKC Inc., Eighty-Four, PA, USA) with a set flow rate of 5 L·min-1 for 3 min. Chemical analyses were completed using a solid-phase microextraction (SPME) (50/30 µm DVB/CAR/PDMS; 2 cm-long fibers, Supelco, Bellefonte, PA, USA) using static extraction for 1 h at room temperature and gas chroma-tography-mass spectrometry (GC-MS) system for analyses (Agilent 6890 GC; Microanalytics, Round Rock, TX, USA). The calibration for butan-1-ol is shown in Figure 4 (illustrated in Lee et al., 2021;).

Photocatalyst (TiO_2) coating

TiO_2 coating was applied in the same way as in the previous study (Lee et al., 2020b). TiO_2 coating on the pre-cut panels for the UV reactor was carried out based on an application protocol provided by PureTi (Cincinnati, OH, USA). In addition, training was provided by SATA (Spring Valley, MN, USA) for accurate spraying control. The temperature (25 ℃) and relative humidity (40-45%) were adjusted to prevent instant evaporation of the sprayed TiO_2 solution (nanostructured anatase 10 µg·cm^{-2} TiO_2, PureTi, Cincinnati, OH, USA) before application. After cleaning the surface of the panel, the TiO_2 solution was sprayed. The spray pressure was adjusted to 60 psi with a regulator from the compressor, and the distance between the panel and the spray was ~0.15 m (6 in) at an angle of 90 deg. Coated panels were dried at room temperature for 3 days.

Data measurement and analysis

The overall mean % reduction (mitigation) for each measured gas was estimated using:

$$\% \, Reduction = \frac{E_{con} - E_{Treat}}{E_{con}} \times 100 \tag{1}$$

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:

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

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 (m^3 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 10^4 = 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 ($mW \cdot cm^{-2}$) and treatment time (ts, s).

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

Statistical analysis

The program of R (version 3.6.2) was used to analyze the mitigation of target standard gases under the UV-A photocatalysis treatment. The mitigation depending on parameters of UV dose and treatment time between control concentration and treatment concentration was 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

NH_3 percent reduction in treated air – effect of UV-A dose controlled by treatment time

The NH_3 percent reduction (%R) was investigated by increasing the UV dose by controlling the treatment time (illustrated in Lee et al., 2021; Table 2). A 5% NH_3 standard gas was injected into the filtration unit inlet (illustrated in Lee et al., 2021; Figure 1) and mixed with ambient air resulting in 67.8 ± 0.2 ppm at the inlet to the mobile laboratory. Initial testing used 60 UV lamps installed in 12 chambers (illustrated in Lee et al., 2021; Figure 1); the NH_3 reduction was investigated by sampling at 3 different treatment times (from 29 to 57 s). The was no significant reduction in NH_3 with the largest UV dose tested (2.2 $mJ \cdot cm^{-2}$). However, the measured concentrations in the control and treatment were reproducible. This observation led us to explore increasing the UV dose by installing additional UV lamps.

NH_3 percent reduction in treated air – effect of UV-A dose controlled by light intensity and time

The NH_3 percent reduction (%R) was investigated by increasing the UV dose by installing additional lamps (from 60 to a total of 160) and maximizing treatment time (illustrated in Lee et al., 2021; Table 3). The additional LED UV-A lamps (110 lamps) using portable UV lamp holders were installed in two chambers (#2 and #3) (illustrated in Lee et al., 2021; Figure 1), and then the number of lamps turn 'on' was controlled.

A statistically significant reduction of 9-11% was measured (illustrated in Lee et al., 2021; Table 3) for UV doses of 3.90 and 5.81 $mJ \cdot cm^{-2}$. Measurement of NH_3 concentration after UV treatment was repeated three times with rapid 'lamps on' & 'lamps off', showing similar mitigation effects (illustrated in Lee et al., 2021; Figure 5). This finding has practical significance because of the simplicity of activating treatment with no apparent lagtime.

Butan-1-ol percent reduction in treated air – effect of UV-A dose controlled by treatment time

As with NH_3, there was no significant percent reduction for the initial 60 lamps turned on in 12 chambers (illustrated in Lee et al., 2021; Table 4). A 100 ppm butan-1-ol standard gas was injected into the filtration unit inlet (illustrated in Lee et al., 2021; Figure 1) and mixed with ambient air resulting in 0.63 ± 0.04 ppm at the inlet to the mobile laboratory and similar concentrations after UV treatment. Still, the measured concentrations in the control and treatment were reproducible. This observation led us to explore increasing the UV dose by installing additional UV lamps for this model VOC.

Butan-1-ol percent reduction in treated air – effect of UV-A dose controlled by light intensity and time

A statistically significant percent reduction (19-41%) in butan-1-ol was found for the UV doses greater than 2.48 $mJ \cdot cm^{-2}$ (i.e., when additional lamps were installed, illustrated in Lee et al., 2021; Table 5). The percent reduction for butan-1-ol was higher than for NH_3. The percent reduction increased with the UV dose. Measurement of butan-1-ol concentration after UV treatment was repeated three times with rapid 'lamps on' & 'lamps off', showing similar mitigation effects (illustrated in Lee et al., 2021; Figure 6), similarly to the effect observed for NH_3. This finding has practical significance because of the simplicity of activating treatment with no apparent lagtime.

Discussion

Evaluation of TiO_2-based UV-A photocatalysis

Previous research on the mitigation of selected target gases via photocatalysis with UV-A in livestock-relevant environmental conditions was summarized in Table 6. In the case of NH_3, the photocatalysis showed a percent reduction from 7% ~ 19% as the light intensity increased in the lab-scale experiment (Lee et al., 2020a;). At the pilot-scale (Lee et al., 2020b;), the reduction with photocatalysis efficiency was reduced to ~5% to 9%. Although the detailed mechanism of photocatalysis varies with different target pollutants, it is commonly agreed that the primary reactions responsible are interfacial redox reactions of the electron (e−) and hole (h+) on the surface of the photocatalyst coating material. Therefore, this is considered that inhibiting factors, such as dust and high humidity, can reduce the interfacial redox reactions on the TiO_2 surface.

In this study, a 9% reduction was observed when the average photocatalysis of light intensity at the photocatalytic surfaces was 0.49 mW·cm-2. Statistically significant NH_3 reduction was observed for sufficiently high light intensity even at shorter treatment times (9.5 s). In the environment of livestock facilities, the NH_3 mitigation using UV-A photocatalysis was found to be less than 20%. This is considered to be less attractive compared to the 50-99% reduction efficiency of other NH_3 mitigation technologies, such as dietary additives, manure additive, manure storage handling, and manure incorporation. (Bittman et al., 2014; Maurer et al., 2016; Ti et al., 2019;). Therefore, based on this and previous research, we do not recommend the use of the UV-A photocatalysis technology in the livestock farm for the only purpose of reducing NH_3.

Depending on the type of VOC, the reduction efficiency varied greatly. It means there was a significant decrease (mitigation) and increase (generation) in some types of VOC. VOCs also showed a higher percent reduction in lab-scale (Lee et al., 2020a; Zhu et al., 2017;) experiments compared with the pilot-scale (Lee et al., 2020b). The photocatalysis showed a percent reduction from 27% ~ 100% in the lab-scale experiment. At the pilot-scale, the reduction with photocatalysis efficiency was reported to be as low as (-53%, generation) to ~62% (mitigation). This decreased percent reduction could result from increased dust and relative humidity for the pilot-scale testing. This study also showed that VOC reduction by UV-A photocatalysis could be reduced with a short treatment time (and therefore the dose), similar to the results of previous studies. The results highlight the requirement to carefully scale up treatments from controlled lab-scale studies into the pilot-scale, and eventually on-farm.

Conclusion

We designed, tested, and commissioned a mobile laboratory for on-farm research and demonstration of UV treatment for gaseous emissions in real farm conditions. The mobile lab is capable of treating up to 1.2 $m^3 \cdot s^{-1}$ of air with TiO_2-based photocatalysis and adjustable UV-A dose based on LED lamps. The commissioning of all systems with standard gases resulted in ~9% and 34% reduction of NH_3 and butan-1-ol, respectively. We demonstrated that as the percent reduction of standard gases increased with increased UV dose by both increased light intensity and treatment time. The environmental conditions of air flowrate, light intensity, standard gas blending were reproducible. The estimation of extrapolated costs of mitigating targeted gases was possible. The TiO_2 coating was adhering to common building materials, but the overall coating integrity and practical reapplication should be investigated in farm-scale trials. The follow-up trials to verify this technology with the mobile UV laboratory on the farm-scale are warranted.

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References

Akdeniz, N., Jacobson, L. D., Hetchler, B. P., Bereznicki, S. D., Heber, A. J., Koziel, J. A., ... & Parker, D. B. (2012a). Odor and odorous chemical emissions from animal buildings: Part 2. Odor emissions. *Transactions of the ASABE*, *55*(6), 2335-2345.

Akdeniz, N., Jacobson, L. D., Hetchler, B. P., Bereznicki, S. D., Heber, A. J., Koziel, J. A., ... & Parker, D. B. (2012b). Odor and odorous chemical emissions from animal buildings: Part 4. Correlations between sensory and chemical measurements. *Transactions of the ASABE*, *55*(6), 2347-2356.

Bereznicki, S. D., Heber, A. J., Akdeniz, N., Jacobson, L. D., Hetchler, B. P., Heathcote, K. Y., ... & Jacko, R. B. (2012). Odor and odorous chemical emissions from animal buildings: Part 1. Project overview, collection methods, and quality control. *Transactions of the ASABE*, *55*(6), 2325-2334.

Bittman, S., Dedina, M., Howard, C. M., Oenema, O., & Sutton, M. A. (2014). Options for ammonia mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen. *NERC/Centre for Ecology & Hydrology*.

Cai, L., Koziel, J. A., Zhang, S., Heber, A. J., Cortus, E. L., Parker, D. B., ... & Lim, T. T. (2015). Odor and odorous chemical emissions from animal buildings: Part 3. Chemical emissions. *Transactions of the ASABE*, *58*(5), 1333-1347.

Costa, A., Chiarello, G. L., Selli, E., & Guarino, M. (2012). Effects of TiO_2 based photocatalytic paint on concentrations and emissions of pollutants and on animal performance in a swine weaning unit. *Journal of Environmental Management*, *96*(1), 86-90.

Guarino, M., Costa, A., & Porro, M. (2008). Photocatalytic TiO_2 coating—To reduce ammonia and greenhouse gases concentration and emission from animal husbandries. *Bioresource Technology*, *99*(7), 2650-2658.

Heber, A. J., Bogan, B. W., Ni, J. Q., Lim, T. T., Ramirez-Dorronsoro, J. C., Cortus, E. L., ... & Casey, K. D. (2009). The national air emissions monitoring study: overview of barn sources. In Livestock Environment VIII, 31 August–4 September 2008, Iguassu Falls, Brazil (p. 28). *American Society of Agricultural and Biological Engineers*.

Koziel, J., Yang, X., Cutler, T., Zhang, S., Zimmerman, J., Hoff, S., . . . Armon, R. (2008). Mitigation of odor and pathogens from CAFOs with UV/TiO_2: Exploring the cost effectiveness. Paper presented at the Proc. *Mitigating Air Emissions from Animal Feeding Operations. Conference Proceedings*, Des Moines, IA. Iowa State University.

Lee, M., Koziel, J. A., Murphy, W., Jenks, W. S., Fonken, B., Storjohann, R., ... & Ahn, H. (2021). Design and testing of mobile laboratory for mitigation of gaseous emissions from livestock agriculture with photocatalysis. *International Journal of Environmental Research and Public Health*, *18*(4), 1523.

Lee, M., Wi, J., Koziel, J. A., Ahn, H., Li, P., Chen, B., . . .& Jenks, W. (2020a). Effects of UV-A Light Treatment on Ammonia, hydrogen sulfide, greenhouse gases, and ozone in simulated poultry barn conditions. *Atmosphere*, *11*(3), 283.

Lee, M., Li, P., Koziel, J. A., Ahn, H., Wi, J., Chen, B., ... & Jenks, W. S. (2020b). Pilot-scale testing of UV-A light treatment for mitigation of NH_3, H_2S, GHGs, VOCs, odor, and O_3 inside the poultry barn. *Frontiers in Chemistry*, *8*, 613, doi.org/10.3389/fchem.2020.00613.

Liu, Z., Murphy, P., Maghirang, R., & DeRouchey, J. (2015). Mitigation of air emissions from swine buildings through the photocatalytic technology using UV/TiO_2. *In 2015 ASABE Annual International Meeting*. American Society of Agricultural and Biological Engineers.

Maurer, D. L., & Koziel, J. A. (2019). On-farm pilot-scale testing of black ultraviolet light and photocatalytic coating for mitigation of odor, odorous VOCs, and greenhouse gases. *Chemosphere*, *221*, 778-784.

Maurer, D. L., Koziel, J. A., Harmon, J. D., Hoff, S. J., Rieck-Hinz, A. M., & Andersen, D. S. (2016). Summary of performance data for technologies to control gaseous, odor, and particulate emissions from livestock operations: Air management practices assessment tool (AMPAT). *Data in brief*, *7*, 1413-1429.

Rockafellow, E. M., Koziel, J. A., & Jenks, W. S. (2012). Laboratory-scale investigation of UV treatment of ammonia for livestock and poultry barn exhaust applications. *Journal of Environmental Quality*, *41*(1), 281-288.

Ti, C., Xia, L., Chang, S. X., & Yan, X. (2019). Potential for mitigating global agricultural ammonia emission: a meta-analysis. *Environmental Pollution*, *245*, 141-148.

Yang, X., Koziel, J. A., Laor, Y., Zhu, W., van Leeuwen, J. H., Jenks, W. S., ... & Armon, R. (2020). VOC removal from manure gaseous emissions with UV photolysis and UV-TiO_2 photocatalysis. *Catalysts*, *10*(6), 607.

Yang, X., Zhu, W., Koziel, J. A., Cai, L., Jenks, W. S., Laor, Y., ... & Hoff, S. J. (2015). Improved quantification of livestock associated odorous volatile organic compounds in a standard flow-through system using solid-phase microextraction and gas chromatography–mass spectrometry. *Journal of Chromatography A*, *1414*, 31-40.

Yao, H., & Feilberg, A. (2015). Characterisation of photocatalytic degradation of odorous compounds associated with livestock facilities by means of PTR-MS. *Chemical Engineering Journal*, *277*, 341-351. doi.org/10.1016/j.cej.2015.04.094.

Zhu, W., Koziel, J., & Maurer, D. (2017). Mitigation of livestock odors using black light and a new titanium dioxide-based catalyst: Proof-of-concept. *Atmosphere*, *8*(6), 103. doi:10.3390/atmos8060103