RESEARCH REPORT
SWINE HEALTH

Title: Mitigation of PRRS transmission with UV light treatment of barn inlet air: proof-of-concept – **NPB #18-160**

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Industry Summary:

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'Drive sustainable Production' is one of the NBP's key goals for 2015-2020 and the Swine Health Committee. This research helped address one key target, i.e., deployment of tools for a significant decrease of porcine reproductive and respiratory syndrome (PRRS) economic impact by 2020. The main objective was to test the efficiency of ultraviolet (UV) treatment of the airborne PRRS virus. Specifically, we tested and compared (in lab-scale) four types of UV lights: (1) conventional germicidal UV-C (254 nm), (2) UV-C' excimer' (222 nm), (3) UV-A (365 nm) fluorescent, and (4) UV-A (365 nm) LED for inactivation of PRRS virus using treatment times that are consistent with fast-moving barn inlet air.

The key advancement was testing of the never-tested before excimer UV-C light that is by far less toxic to people and livestock while being very recently proven to be bactericidal for MSRA and for the H1N1 influenza virus. No data existed on how effective the excimer UV-C is for the treatment of PRRS. Similarly, no data existed on how effective the UV-A (a.k.a. 'black light' and commonly used for artificial suntanning) is for PRRS treatment. Yet, there are concerns about using the UV 254 nm (conventional germicidal UV lamps) on farms due to its harm to both workers and animals.

The experimental design consisted of PRRS virus propagation and storage, PRRSV aerosolization, UV treatment, PRRSV sampling and recovery, virus isolation, determination of surviving virus, estimation of UV dose, and cost analysis to achieve practical levels of virus load reduction.

The results showed that UV-C (254 nm) and UV-C excimer (222 nm) could effectively inactivate the aerosolized PRRS virus. The UV-A (365 nm, both fluorescent and LED), however, did not yield obvious virus load reduction in this research for doses up to 4.11 mJ/cm^2. UV inactivation models of four lamps were developed based on the experimental data to estimate UV doses for target virus load reduction.

A UV dose needed for 2-log (99%), 3-log (99.9%) aerosolized PRRS virus reduction was 0.0872 and 0.0958 mJ/cm^2, respectively, for UV-C (254 nm). This finding is also important because the value for the 3-log (99.9%) PRRS virus reduction was over 12x lower than the one and only previously reported 3-log (99.9%) airborne (not in plate study) PRRS virus reduction by 1.21 mJ/cm^2 for UV-C (254 nm) (Cutler et al., 2012).

The practical significance is that the UV-C (254 nm) doses (and therefore the cost) might be lower than previously estimated. The dose needed for 2-log (99%), 3-log (99.9%) aerosolized PRRS virus reduction was 0.0429 and 0.0489 mJ/cm^2, respectively, for UV-C (222 nm, excimer). This finding is important because the 222 nm 'excimer' UV doses are ~50% lower than the conventional 254 nm for the same level of PRRS virus kill. However, the cost of 222-nm excimer lamps is still economically prohibitive to consider them for the scaling-up trials.

Pilot-scale testing of UV-C treatment of aerosolized PRRS large volumes of air simulating barn ventilation rates are recommended based on the high effectiveness and reasonable cost estimates comparable to HEPA filtration.

Key Findings:

a. UV-C (254 nm) and UV-C excimer (222 nm) could effectively reduce airborne PRRSV >99% with a short treatment time (<2 s) when lamps are within 4 in (10 cm) of fast-moving air.
b. The UV dose needed for a 99.9% PRRSV reduction was 0.0872 mJ/cm^2 and 0.0429 mJ/cm^2 for UV-C (254 nm) and UV-C (222 nm), respectively.
c. Under UV-A (365 nm, fluorescent) and UV-A (365 nm, LED) treatment, no noticeable PRRSV reduction was found for the doses tested (up to 4.11 mJ/cm^2)
d. Preliminary economic analysis showed that for a 1000-head swine barn, UV light application has a similar cost compared to HEPA filters (considering materials + electricity).

Keywords: airborne pathogens, animal production, biosecurity, swine health, porcine reproductive and respiratory syndrome, swine diseases, ultraviolet light, pathogen load

Scientific Abstract:

Porcine reproductive and respiratory syndrome (PRRS) is an infectious swine disease that causes significant economic loss to swine producers every year. PRRSV aerosols are an important route of transmission. Proper treatment of infectious air could potentially mitigate the spread of the disease from one barn to another. This project involved designing, building, and testing a lab-scale apparatus for mitigating aerosolized PRRSV with UV light treatment. UV lights of three wavelengths, blacklight (365 nm) UV-A (both fluorescent and LED-based lamps), "excimer" UV-C (222 nm), which was proven to be almost innocuous to mammalian skin while being germicidal, and conventional germicidal UV-C (254 nm) were tested for their ability to inactivate airborne PRRSV. The airborne PRRS virus was irradiated in fast-moving air with short treatment times (<2 s). Treated PRRSV aerosols samples were collected and titrated using standard virological techniques, and the results of the experiment were expressed as 50% tissue culture infective dose per milliliter ($TCID_{50}$/mL) using the Spearman-Karber method. The results showed that UV-C (254 nm) and UV-C excimer (222 nm) could effectively inactivate the aerosolized PRRS virus. The UV inactivation model was developed based on experimental data to estimate UV doses. A UV dose needed for 2-log (99%) & 3-log (99.9%) aerosolized PRRS virus reduction was 0.0872 & 0.0958 mJ/cm^2, respectively, for UV-C (254 nm). This finding is also important because the value for the 3-log (99.9%) PRRS virus reduction was over 12x lower than

the one and only previously reported 3-log (99.9%) PRRS virus reduction by 1.21 mJ/cm^2 (Cutler et al., 2012). The practical significance is that the UV-C (254 nm) doses (and therefore the UV treatment cost) might be lower than previously estimated. The UV-C (222 nm, excimer) dose needed for 2-log (99%) and 3-log (99.9%) aerosolized PRRS virus reduction was 0.0429 and 0.0489 mJ/cm^2, respectively. This finding is important because the 222 nm 'excimer' UV doses were more than 50% lower than the conventional 254 nm for the same level of PRRS virus kill. However, the cost of 222-nm excimer lamps is still economically prohibitive to consider them for the scaling-up trials. The UV-A (365 nm, both fluorescent and LED) could not reduce virus load for tested doses up to 4.11 mJ/cm^2. Pilot-scale or farm-scale testing of UV-C treatment of aerosolized PRRS large volumes of air simulating barn ventilation rates are recommended based on the high effectiveness of PRRS inactivation and reasonable cost estimates comparable to HEPA filtration.

Introduction:

List of research questions (from the proposal):
- What is the effectiveness of UV-A, UV-C, and UV-254 nm treatment of airborne PRRS virus?
- What are the effects of treatment time, light intensity, electric power input on UV treatment?
- Is UV (-A, -254 nm, and -C) treatment feasible for scale-up to treat barn inlet air?
- What is the treatment cost based on lab-to-farm scale-up of UV treatment of PRRS?
- Would the proposed UV treatment be capable of significantly reducing the current cost of HEPA filtration?
- Is UV treatment feasible for all types of swine production housing?

Air and aerosols are an important route of transmission for some infectious diseases. Infectious aerosols can carry pathogens (bacteria, viruses) and transmit them from one place to another or one body to another. Common diseases such as foot-and-mouth disease (FEDV) (Donaldson et al., 2002) and influenza (Herfst et al., 2012) rely on airborne transmission.

Porcine reproductive and respiratory syndrome (PRRS) is one of the most economically impactful diseases that need to be mitigated to ensure the security of animal production. The annual cost of PRRS disease to the producers was estimated to be $664 million in 2012 (Holtkamp et al., 2013), which is a 19% increase from $560 million estimated in 2005 (Neumann et al. 2005). The disease is caused by a single-stranded RNA virus, PRRS virus (PRRSV), initially described by Terpstra et al. (1991) and Wensvoort et al. (1991). The disease has two overlapping clinical symptoms, reproductive failure or impairment, as well as respiratory diseases.

PRRSV can be transmitted via indirect contact (such as aerosol and fomites) or direct contact (such as pig-to-pig). It was found that aerosols generated during swine respirations can be infectious to surrounding pigs at a range of a few meters (Wills et al. 1997; Torremorell et al. 1997) to several kilometers (Otake et al. 2002; Lager and Mengeling 2000). Some later research suggested that PRRSV aerosols can travel a long distance (~9 km) and remain infectious (Dee et al., 2009; Otake et al., 2010). The meteorological conditions that favor the long-distance transmission of airborne virus included low temperature, moderate levels of relative humidity, a rising barometric pressure, low wind speed, as well as low sunlight intensity (Dee et al. 2010). It was reported that PRRSV could be infectious for 24 hours at 37 ℃ (or 98.6 ℉) and survive for 6 days at 21 ℃ (or 70 ℉) (Pitkin et al.). Given its airborne features and survivability, proper treatment of PRRSV aerosols could effectively reduce the transmission of the disease.

Hermann et al. (2006) optimized a sampling system with six channels for simultaneous PRRSV aerosol recovery and detection. Different sampling devices, parameters, and conditions were compared for optimal airborne virus sampling. Cutler et al. (2012) built upon it by establishing a PRRSV aerosolization and treatment system with four channels (quartz tubes) for UVC disinfection. Another means of mitigating PRRSV was reported by La et al. (2019), where air ionization was applied on viral aerosols. Systems regarding aerosolization, inactivation, and collection of aerosols were also utilized in

studies of other airborne viruses. Welch et al. (2018) established an aerosol exposure chamber (one-channel) where influenza virus was aerosolized, treated by UV, and then collected.

There is still a knowledge gap and a need to develop realistic mitigation technologies for airborne aerosols such as PRRSV. The mitigation technologies require controlled setups that are simulating environmental conditions that may influence the survival of the airborne virus. We were motivated by the scarcity of research on aerosolized PRRS and potential limitations of previous data collected without real-time monitoring of an aerosolization system, especially airflow rate and pressure that are needed to generate and recover the virus.

Ultraviolet (UV) light, which is a range of wavelength that is shorter than the visible light spectrum, has been proven to disinfect or inactivate pathogens at a certain wavelength; on the other hand, it can potentially reduce the operational and capital costs, and it uses smaller physical footprint in a barn building compared to HEPA filters. To date, very little research has been published on the use of UV for aerosolized PPRSV inactivation. Cutler et al. (2012) remain the benchmark study, where they used the UV-C germicidal (254 nm) light on the treatment of aerosolized PRRSV. However, the data on the range of UV dose needed to inactivate different logs of PRRSV remains very limited.

One of the key advancements in this research was the testing of excimer UV-C on PRRSV. The excimer lamp (207 – 222 nm) is by far less harmful to people and livestock compared with 254-nm UV-C while being very recently proven to be germicidal for Methicillin-resistant Staphylococcus aureus (MRSA) (Buonanno et al., 2017) and for the H1N1 influenza virus (Welch et al., 2018). We chose this light because it is innocuous to mammalian skin (Welch et al., 2018). No data exists on how effective the Excimer UV-C is for the treatment of PRRSV. Similarly, no data exists on the effectiveness of the UV-A (365 nm) (commonly known as 'black light' and used for artificial sun tanning). Yet, the potential use of UV 254 nm (considered to be germicidal) on farms is questionable due to concerns about its harmful effect on both workers and animals. We tested and compared three wavelengths of UV light (UV-A 365 nm under fluorescent and LED categories, UV-C 254 nm, and excimer UV-C at 222 nm) for treatment of PRRSV.

Objectives:
The main objective of this research was to test the efficiency of UV light for the treatment of airborne PRRS virus. Specifically, we tested and compared (in lab-scale) two novel UV lights: (1) 'excimer' UV-C (207-222 nm), (2) black light (UV-A) vs. conventional bactericidal UV (254 nm) for inactivation of PRRS virus using treatment times that are consistent with fast-moving barn inlet air.

Intended outcomes (objectives)

1. The effectiveness of blacklight UV-A, excimer UV-C, and UV-254 nm treatment of airborne PRRS virus.
2. The effectiveness of UV treatment as a function of treatment time, light intensity, electric power input.
3. Evaluation of the feasibility of UV (-A, 254 nm, and -C) treatment for scale-up to treat barn inlet air.
4. An economic analysis based on a lab-to-farm scale-up of UV treatment of PRRS.
5. Cost comparison of current HEPA filtration vs. proposed UV treatment.
6. Peer-reviewed manuscript, final report, media, and Extension materials.
7. Sufficient experimental data to make an informed decision about the feasibility of UV treatment on a farm-scale.

Materials & Methods:

1. Experiment Setup

The system (Figure 1) consisted of three major sections: aerosolization section, treatment section, and sampling section, following the direction of the airflow. The aerosolization section was

responsible for generating PRRSV aerosols that were to be introduced to the treatment section, and it included the air compressor (built-in with the fume hood), a pressure regulator, pressure gauges, a mass flow controller, a Collison nebulizer with the addition of a pressure gauge, and a glass container. The treatment section was designed to be used for subsequent aerosol treatment experiments.

The PRRS sampling section was where the aerosols were collected in the sampling media. It consisted of manifold 2 with eight branches connected to eight flowmeters, eight glass impingers (, pressure gauges, a mass flow meter (MFM), and a vacuum pump. All sections had sensors on temperature and relative humidity installed.

As seen in Figure 1, compressed air supplied by the fume hood passed to a Collison nebulizer to pressurize the PRRSV inoculum and then generate the aerosols. The nebulizer was prefilled with PRRSV inoculum with antifoam emulsion, which was selected because it was proven to be innocuous to animal cells and PRRSV (Hermann et al. 2006) but can help reduce the foaming effects. Viral aerosols were then directed to the glass container and then into Manifold 1, where they were distributed into eight branches, with each connected to a quartz tube. The rear (right side) end of each quartz tube was connected to an impinger where the aerosols were captured.

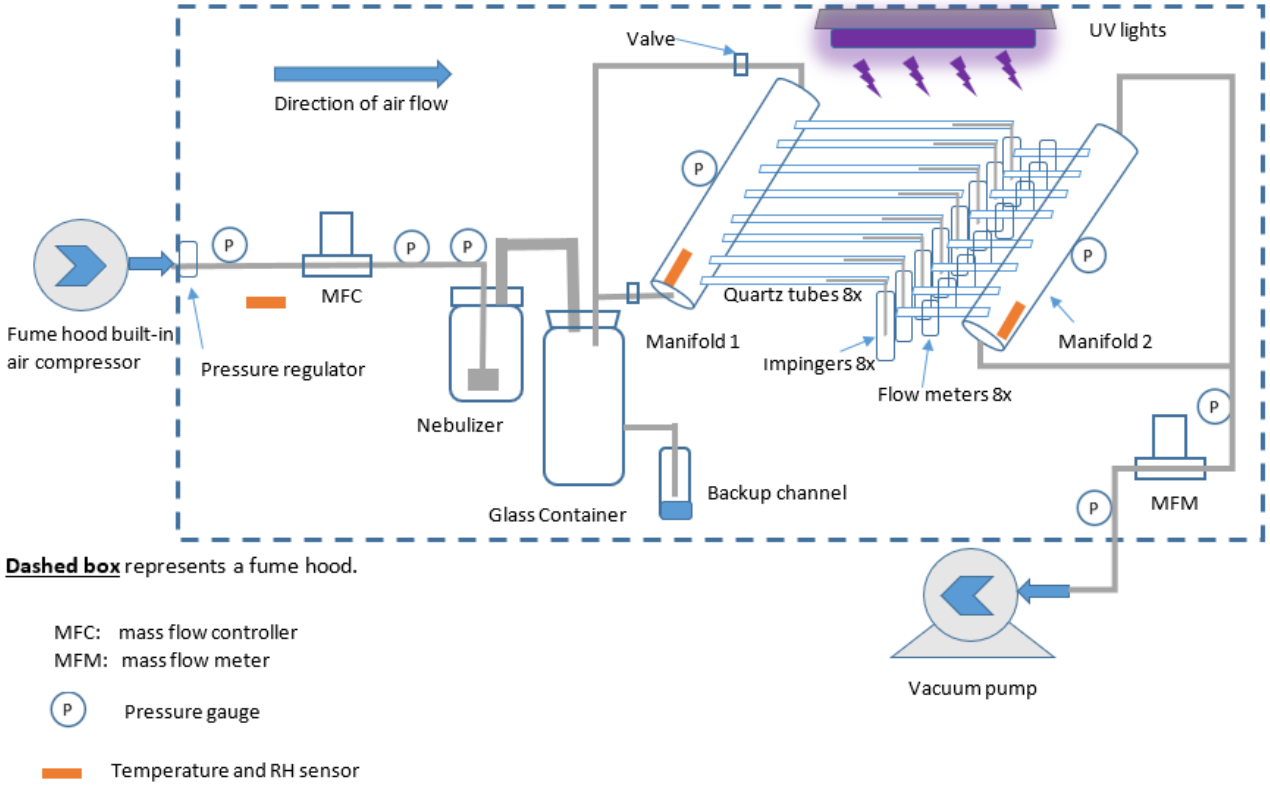

Figure 1. Experimental setup for generation and collection of airborne PRRSV inside a fume hood. The built-in air compressor in the fume hood was responsible for pressurizing air flowing into the system, and the right-side pump was vacuuming exhaust air coming out of the system. (MFC = mass flow controller; MFM = mass flow controller.)

2. UV light irradiance and dose measurements

Four types of UV lights with three different wavelengths were used in this experiment: i) 365-nm UV-A fluorescent light (Ushio America Inc., Cypress, CA, USA), ii) 365-nm UV-A LED lights (Once Inc., Plymouth, MN, USA), iii) 222-nm UV-C "excimer" lights ((Ushio America Inc., Cypress, CA,

USA)), and iv) 254-nm germicidal UV-C lights (Ushio America Inc., Cypress, CA, USA). The light intensity was measured by ILT 1700 radiometer with wavelength-specific sensors and filters (±5 nm range).

3. UV treatment of aerosolized PRRS Virus

Eight identical quartz tubes (ID = 25 mm, OD = 28 mm) were positioned horizontally with an equal gap between each other. The UV lights were placed on top of the tubes, 10 cm away from the central horizontal plane. Different treatments were implemented for the eight tubes, i.e., shielding different lengths by PVC pipes to achieve various UV treatment times. The corresponding treatment time ranged from 0.258 to1.806 seconds, respectively.

The Bunsen-Roscoe Reciprocity Law dictated the estimation of the UV dose:

$$D = I \times T \quad \text{Eqn. [1]}$$

where D is the UV dose (mJ/cm^2), I is irradiance or light intensity (mW/cm^2) and T is the UV treatment time (s). The UV doses of different treatments are shown in the Results section.

4. PRRSV isolation and virus titer determination

The virus used in this experiment is a type 2 PRRS virus isolate, MN-184 (Lineage 1), initially provided by the Veterinary Diagnostic Laboratory (College of Veterinary Medicine, Iowa State University). The virus was propagated in the MARC-145 cell line (Kim et al. 1993). MARC-145 cells were cultured in the regular RPMI-1640 medium supplemented with the final concentrations of 10% fetal bovine serum, 2 mM L-glutamine, 0.05 mg/mL gentamicin, 100 unit/mL penicillin, 100 µg/ml streptomycin, and 0.25 µg/mL amphotericin. Large-scale virus propagation was eventually conducted on 5-layer flasks. Approximately three liters of virus inoculum were harvested in the end, averaging at a virus titer of median tissue culture infective dose per ml ($TCID_{50}$/mL) of 5.5 [$\log_{10}$ based]. The inoculum was then thoroughly mixed to ensure homogeneity before being distributed into 30 ml aliquots. Propagated PRRS virus was then stored in freezers at -80 °C throughout the duration of the experiment and used as needed.

After the airborne PRRS sample collection was finished, impinger fluid was immediately transferred to a biosecurity cabinet in a BSL-2 lab for serial dilutions. A 10-fold serial dilution was performed with eight replicates for each sample on 96-well plates.

Cytopathic effect (CPE) development was checked under a microscope daily, and infected wells were marked as positive until no more additional wells were identified as infected. That process usually took between 5 and 7 days. Plates were read under a fluorescent microscope.

The Spearman-Karber Method was used to calculate the virus titers, which were based on the number of wells showing positive PRRSV-specific fluorescence at specific dilution. The results were expressed as 50% tissue culture infectious dose ($TCID_{50}$/mL) of the collected impinger fluid.

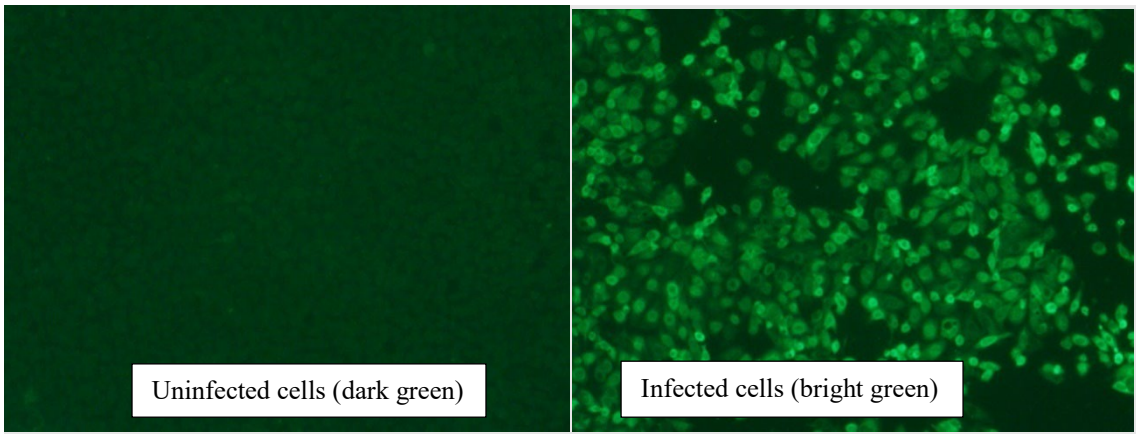

Figure 2. After 5~7 days of incubation, the MARC-145 cell plates were fixed and stained by PRRSV conjugate. Both pictures show stained cells with 6 days of incubation after the addition of PRRSV aerosol samples.

5. Data analysis of UV inactivation (modeling)

The statistical analysis was conducted using the R program. The inactivation curves shown in the Results section were modeled using the equations mentioned in Cutler et al. (2011) and Riley et al. (1973). It is assumed that the one-stage inactivation model treats the PRRSV as a homogeneous group with the same susceptibility to UV treatment. The two-stage inactivation model categories PRRSV as two groups, one is a susceptible group, and the other is the resistant group with regards to the susceptibility to UV light.

In this research, both one and two-stage inactivation curves were modeled and analyzed.

One-stage model (derived from Chick's law),

$$log_{10}N_t = log_{10}N_0 - kD_t + C_1 \text{ Eqn. [2]}$$

Rearranging Eqn. [2] to get the fraction of surviving pathogens (log_{10} normalized),

$$log_{10}\frac{N_t}{N_0} = -kD_t + C_1 \text{ Eqn. [3]}$$

where:
N_t= virus titer ($TCID_{50}/mL$) in the impinger fluid after UV treatment with doses D_t
N_0= virus titer ($TCID_{50}/mL$) in the control sample (without UV exposure)
k = inactivation rate (constant)
D_t= UV dose (mW/cm^2), calculated by Eqn. [1]
C_1= intercept for the one-stage model.

A two-stage model can be expressed as,

$$log_{10}N_t = log_{10}N_0 + log_{10}[(1-f)\cdot 10^{-k_1\cdot D_t} + f\cdot 10^{-k_2\cdot D_t}] + C_2 \text{ Eqn. [4]}$$

Rearranging Eqn. [4] to get the fraction of surviving pathogens (log_{10} normalized),

$$log_{10}\frac{N_t}{N_0} = log_{10}[(1-f)\cdot 10^{-k_1\cdot D_t} + f\cdot 10^{-k_2\cdot D_t}] + C_2 \text{ Eqn. [5]}$$

where:
N_t= virus titer ($TCID_{50}/mL$) of the impinger fluid from treatments of UV inactivation with doses D_t
N_0= virus titer ($TCID_{50}/mL$) of the impinger fluid from the controlled treatment (without UV exposure)
$\frac{N_t}{N_0}$ = the survival fraction of PRRSV

$1-f$ = the fraction of virus population that is more susceptible to UV inactivation with inactivation rate k_1
f = the fraction of virus population that is more resistant to UV inactivation with inactivation rate k_2
k_1 = inactivation rate for a fraction of virus population that is more susceptible to UV inactivation
k_2 = inactivation rate for a fraction of virus population that is more resistant to UV inactivation
D_t = UV dose (mW/cm^2), calculated by Eqn. [1]
C_2= intercept for the two-stage model.

Results:

Objective 1. **The effectiveness of blacklight UV-A, excimer UV-C, and UV-254 nm treatment of airborne PRRS virus.**

Main findings:

- The UV-C (254 nm) dose needed for 1-log (90%), 2-log (99%), and 3-log (99.9%) aerosolized PRRS virus reduction was 0.0681, 0.0872 and 0.0958 mJ/cm^2, respectively.
- The UV-C (222 nm, excimer) dose needed for 1-log (90%), 2-log (99%), and 3-log (99.9%) aerosolized PRRS virus reduction was 0.0240, 0.0429 and 0.0489 mJ/cm^2, respectively.
- There was no effectiveness found for UV-A (365 nm), both fluorescent and LED-based irradiation up to 4.11 mJ/cm^2.
- The PRRS inactivation model for UV-C was developed based on the one-stage and two-stage mechanisms. PRRS inactivation constants (k) were estimated. Both the one-stage and two-stage models are useful for scaling up UV treatment of PRRS and comparisons to other related UV research on pathogen disinfection.

Table 1. Summary of estimated UV dose for aerosolized PRRSV inactivation based on the one-stage and two-stage models.

Estimated UV dose (mJ/cm^2) needed for target % aerosolized PRRS virus reduction in fast-moving air								
UV Type	90% (1-log)		99% (2-log)		99.9% (3-log)		99.99% (4-log)	
	1-stage	2-stage	1-stage	2-stage	1-stage	2-stage	1-stage	2-stage
UV-C (254 nm)	0.109	0.0681	0.315	0.285	0.521	1.027 [a]	0.727	1.771
UV-C (222 nm)	0.028	0.024	0.058	0.047	0.088	0.071	0.118	0.095
UV-A (365 nm, fluorescent)	-58.42[b]	5.59	-122.68 [b]	12.95	-186.95 [b]	20.31	-251.22 [b]	27.67
UV-A (365 nm, LED)	-49.65[b]	59.61	-95.46 [b]	107.80	-141.27 [b]	156.00	-187.08 [b]	204.19

[a] UV-C (254 nm) dose needed to inactivate 99.9% aerosolized PRRSV was estimated to be 1.21 mJ/cm^2 by Cutler et al. 2012.
[b] Negative values as such are not considered meaningful, i.e., these categories of UV light did not have an inactivation effect under these scenarios.

Table 2. One-stage and two-stage models (Eqn. [2] and Eqn. [4], respectively), parameter estimations and model parameters for inactivation of airborne PRRSV with four types of UV light tested. Critical (meaningful) inactivation constants (k values) are in bold.

Model Parameters	**UV-C (254 nm)**	**UV-C (222 nm)**	**UV-A**	**UV-A (365 nm,**

			(365 nm, fluorescent)	LED)
Two-stage inactivation model				
Intercept	-0.0603	0.03226	0.012422	-0.02748
Resistant virus population fraction (***f***)	0.97595	0.99945	0.57417	1.72542
Susceptible virus population fraction (**1-*f***)	0.02405	0.00055	0.42583	-0.72542
Inactivation rate (constant),k_1, for susceptible virus population	**-1.34467**	**-24.1466**	2.89537	0.88296
Inactivation rate (constant), k_2, for resistant virus population	**15.55614**	**42.39715**	-0.13585	0.02075
Lack-of-fit test ***p*-value**	p = 0.228	p = 0.8922	p = 0.2848	p = 0.6532
One-stage inactivation model				
Intercept	-0.4727	-0.06694	-0.09103	0.08388
Inactivation rate, ***k***	4.8512	33.2674	-0.01556	-0.02183
Lack-of-fit test ***p*-value**	p = 0.006781	p = 0.1813	p = 0.3336	p = 0.7748

Objective 2. **The effectiveness of UV treatment as a function of treatment time, light intensity, electric power input.**

Main findings:

- The functions (models) that describe the effectiveness of UV treatment for each type of UV light were listed below. Since two-stage models fit better (more accurate) with the data because of higher lack-of-fit p-values, only two-stage models were included in this report.

For UV-C (254 nm),

One-stage model: $log_{10}\frac{N_t}{N_0} = 4.8512 \cdot D_t - 0.4727$

Two-stage model: $log_{10}\frac{N_t}{N_0} = log_{10}[0.02405 \cdot 10^{-1.34467 \cdot D_t} + 0.97595 \cdot 10^{15.55614 \cdot D_t}] - 0.0603$

For UV-C (222 nm),

One-stage model: $log_{10}\frac{N_t}{N_0} = 33.2674 \cdot D_t - 0.06694$

Two-stage model: $log_{10}\frac{N_t}{N_0} = log_{10}[0.00055 \cdot 10^{-24.1466 \cdot D_t} + 0.99945 \cdot 10^{42.39715 \cdot D_t}] + 0.03226$

For UV-A (365 nm, fluorescent),

One-stage model: $log_{10}\frac{N_t}{N_0} = -0.01556 \cdot D_t - 0.09103$

Two-stage model: $log_{10}\frac{N_t}{N_0} = log_{10}[0.42583 \cdot 10^{2.89537 \cdot D_t} + 0.57417 \cdot 10^{-0.13585 \cdot D_t}] + 0.012422$

For UV-C (365 nm, LED),

One-stage model: $log_{10}\frac{N_t}{N_0} = 0.02183 D_t + 0.08388$

Two-stage model: $log_{10}\frac{N_t}{N_0} = log_{10}[-0.72542 \cdot 10^{0.88296 \cdot D_t} + 1.72542 \cdot 10^{0.02075 \cdot D_t}] - 0.02748$

Note: UV treatment time and light intensity were incorporated into the UV dose (see Eqn. [1] $D = I \times T$, *where dose = light intensity × treatment time).* The relationship between electric power input and the effectiveness of treatment was not studied independently, but electric power input could be

viewed to change in synchronization with the change of the UV light intensity, so it was unnecessary to repeat the study on electric power input.

A visual presentation showcasing the effectiveness of UV treatment (in terms of PRRSV survival %) related to treatment time, light intensity by UV-C (254 nm), UV-C excimer (222 nm), UV-A (365 nm, fluorescent), or UV-A (365 nm, LED) is presented in Figure 1 – 3 below. UV inactivation model curves (one-stage and two-stage) were included in each of the figures.

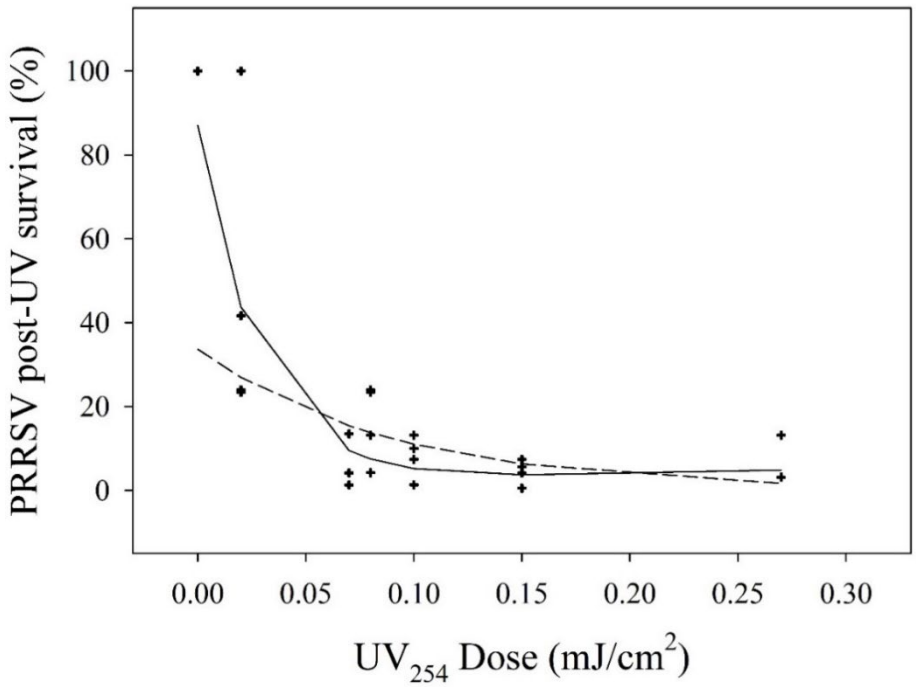

Figure 1. UV-C (254 nm) treatment inactivation curve on aerosolized PRRSV. One-stage (dashed line) and two-stage (solid line) inactivation curves were drawn.

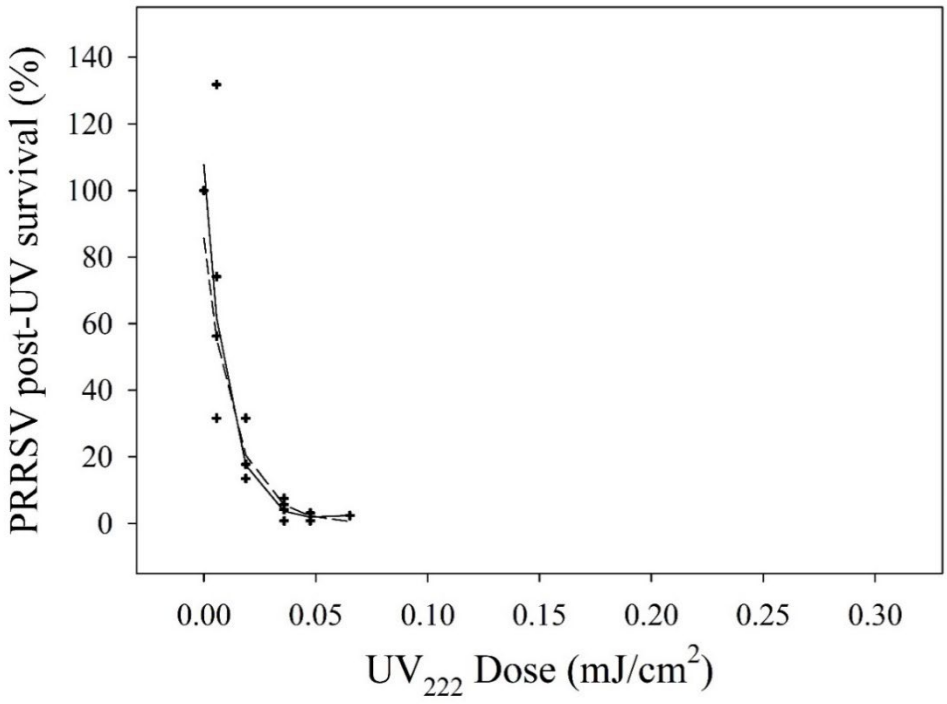

Figure 2. UV-C (222 nm) treatment inactivation curve on aerosolized PRRSV. One-stage (dashed line) and two-stage (solid line) inactivation curves were drawn.

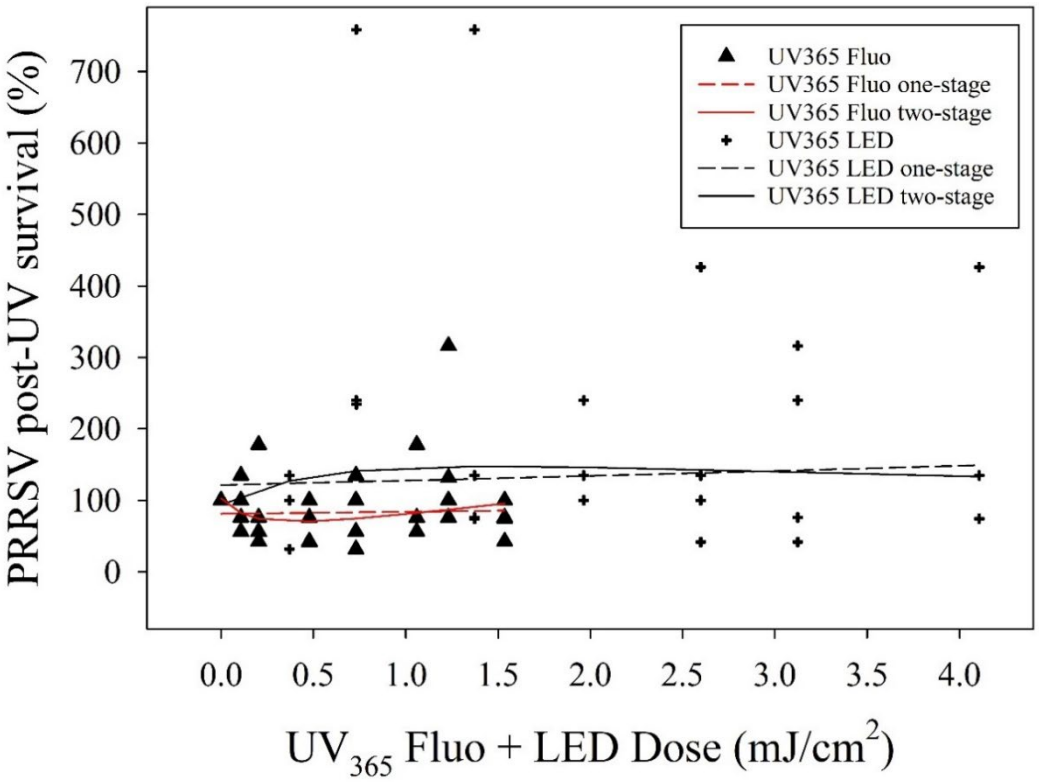

Figure 3. UV-A (365 nm, fluorescent and LED) treatment inactivation curve on aerosolized PRRSV. One-stage (dashed line) and two-stage (solid line) inactivation curves were drawn.

Objective 3. Evaluation of the feasibility of UV (-A, 254 nm, and -C) treatment for scale-up to treat barn inlet air.

Main findings:

- Preliminary economic analysis showed that for a 1000-head swine barn, UV light application has a similar cost compared to HEPA filters (considering materials + electricity).

The feasibility of UV for scale-up was evaluated in two aspects: 1) effectiveness (already addressed in Objective 2) and 2) cost.

2) A preliminary economic analysis of UV for farm-scale applications was described under Objective 4 and Objective 5 in greater detail. The analysis shows that the cost of a UV light system for a 1000-head swine barn (sows and boars) is estimated to be $107,600, while the cost for HEPA filters under the same condition is $88,440. Since the cost difference between the two applications is within 20%, it would not hinder barns already equipped with HEPA or about to install HEPA filters to switch to UV light applications.

Objective 4. An economic analysis based on lab-to-farm scale-up of UV treatment of PRRS.

(1) Lab-scale experiment (this research)

Major Assumptions:

a) 1 $TCID_{50}$ = 1 PRRSV airborne particle.
b) PRRSV particles are countable and homogeneous.

c) The UV light efficiency (the ratio of UV watts over total watts consumption) is 32.7%, estimated based on Ushio G15T8 UV lamp and assumed this value for all UV light used in this calculation.
d) The electricity cost in Midwest US is $0.12/kWh.

Table 3. Theoretical cost of energy and electricity on PRRSV virus titer $TCID_{50}$ reduction. The estimations were based on the data collected in this research. This analysis was conducted based on the assumption $TCID_{50}$ is quantifiable, countable values that could indicate the number of PRRSV particles.

Types of UV	**PRRSV inactivated per J ($TCID_{50}$/J) ***	**PRRSV inactivated per kWh ($TCID_{50}$/kWh) ****	**PRRSV inactivated per $ ($TCID_{50}$/$) *****
UV-C (254 nm)	1.21×10^{10}	4.36×10^{16}	2.23×10^{17}
UV-C (222 nm)	3.62×10^{10}	1.31×10^{17}	6.11×10^{17}
UV-A (365 nm, fluorescent)	N/A	N/A	N/A
UV-A (365 nm, LED)	N/A	N/A	N/A

* The estimated number of PRRSV inactivated per Joule (J) of electricity (see assumption c).
** The estimated number of PRRSV inactivated per kilowatt-hour (kWh) of electricity consumed by lamps.
*** The estimated cost (in USD) of electricity needed to inactivate a number of airborne PRRSV particles.

Table 4. Comparison of electricity cost (operational cost) among four different types of UV light used for this lab-scale experiment. The experiment time was 45 min.

UV light	**Power Consumption (W)**	**% area of effective UV irradiation**	**Effective power consumption (W)**	**Electricity consumption (kWh)**	**Electricity Cost ($)***	**Hardware cost ($)****
UV-C (254 nm)	50.5	52%	26.3	0.0197	$0.0023	$100
UV-C (222 nm)	250	56%	138.8	0.1041	$0.0122	$3,000
UV-A (365 nm, fluorescent)	49.5	52%	25.6	0.0192	$0.0022	$100
UV-A (365 nm, LED)	43.8	50%	21.9	0.0165	$0.0019	$1,000***

*Electricity cost in rural areas (US Midwest) = $0.12/kWh.
**Cost of UV lamps and fixtures, excluding other experimental devices, as described in the Material and Methods section.
***Cost estimation of a research-grade prototype of an LED lamp (LED board + power supply).

(2) Preliminary cost estimation of farm-scale UV application

Table 5. Assumptions and data used to estimate a farm-scale application*.

			Ventilation rate (CFM/pig)		Total ventilation rate (CFM)	
Swine Type	Head (unit)	Weight (lb)	Cold weather	Hot weather	Cold weather	Hot weather
Sow and Litter	910	400	20	500	18,200	455,000
Boars & Breeding Sows	90	400	14	300	1,260	27,000

*Data related to swine barn layout and ventilation rate was obtained from MWPS-8 "Swine Housing and Equipment Handbook," MidWest Plan Service, Ames, Iowa. The ratio of boars to sows is assumed to be 1:10 based on an example provided in the MWPS-8.

Table 6. An estimate of the cost needed for a farm-scale UV application.

	Total material cost $ (hot weather)	1-year electricity cost $ (mixed weather)	Maintenance cost ($)	Total cost $
UV light	$66,000	$35,000	$6,600	$107,600

Objective 5. **Cost comparison of current HEPA filtration vs. proposed UV treatment.**

Main findings:

- The estimated cost for 1-year implementation of UV-C (254 nm) lamps is $107,600, while for HEPA filters, the cost is $88,000.

Table 7. Estimation of the cost of implementing UV light treatment in a 1000-head swine barn with different swine types for a 1-year period. Estimations are based on extrapolations from this lab-scale study.

Type	Total material cost $ (hot weather)	1-year electricity cost $ (mixed weather)	Maintenance cost ($)	Total cost $
UV light	$66,000	$35,000	$6,600	$107,600
HEPA filters	$80,400	N/A	$8,040	$88,440

The estimations are based on the assumptions that:
1) One HEPA filter can take up to 600 CFM.
2) The UV lamps have a lifetime of at least 8,000 hours (assuming to be 1 year).
3) The maintenance cost is estimated to be 10% of the material cost.
4) The material cost is based on the hot weather conditions (higher ventilation rate) while the electricity cost is calculated based on mixed (hot and cold) weather condition to reflect real natural conditions.

Objective 6. **Peer-reviewed manuscript, final report (this document), media, and Extension materials).**

There are currently two manuscripts in preparation. Their working citations are:

- Manuscript 1: Li, P., Koziel, J.A., Zimmerman, J.J., Hoff, S.J., Zhang, J., Cheng, T., Yim-Im, W., Lee, M., Chen, B., Banik, C., Jenks, W.S. Method and protocol for aerosolization and collection of PRRSV for determinations: theoretical and engineering considerations. *Frontiers in Bioengineering and Biotechnologies.*
- Manuscript 2: Li, P., Koziel, J.A., Zimmerman, J.J., Zhang, J., Cheng, T., Yim-Im, W., Lee, M., Chen, B., Hoff, S.J., Jenks, W.S. Mitigation of Airborne PRRSV Transmission with UV Light Treatment of Barn Inlet Air: Proof-of-concept. *Frontiers in Microbiology.*

The e-newsletter with a 500-600 words summary about the findinings in this project for the National Hog Farmer magazine is scheduled for January 29, 2021.

Additional media and Extension related materials will be developed based on peer-reviewed and published Manuscripts 1 and 2.

Objective 7. Sufficient experimental data to make an informed decision about the feasibility of UV treatment on a farm-scale.

Based on the findings under Objective 1, Objective 2, and Objective 5, it is concluded that farm-scale or pilot-scale testing of UV-C treatment of aerosolized PRRS with fast-moving air (simulating barn ventilation rates) are recommended based on the high effectiveness and reasonable cost estimates comparable to HEPA filtration.

Discussion:

The experimental data shows that the UV chamber can achieve a maximum reduction of >99.9% (3-log) with a dose <0.3 mJ/cm^2 for UV-C (254 nm) dose, or <0.08 mJ/cm^2 for UV-C (222 nm). For both UV lights of UV-A (365 nm), the reduction of PRRSV titer was not found with the UV dose used in this experiment. This experiment does not rule out the effectiveness of UV-A, but a much higher UV dose may be needed to achieve the same log reduction, or it may never be possible to have a significant germicidal effect.

The experimental data were used to fit with inactivation models (both one-stage and two-stage) for all four types of UV light used in this experiment. It appears to be that two-stage models fit better with both UV-C 254 nm and UV-C 222 nm. The models could be used to predict the UV dose needed for a % reduction of airborne PRRSV or to predict a % of PRRSV reduction based on a known UV dose. The data and models generated in this research could also be beneficial for comparison with similar studies on other types of viruses.

Preliminary economic analysis showed that the cost of a UV light system for a 1000-head swine barn (sows and boars) is estimated to be $107,600, while the cost for HEPA filters under the same condition is $88,440. Since the cost difference between the two applications are within 20%, it would not (theoretically) hinder barns already equipped with HEPA from switching to UV light applications. However, more data and research are needed to make more accurate and informative long-term predictions.

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