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Application of LED-based degradation technology for harmful substances during the growing to finishing stages in an enclosed water-curtain-type SPF pig farm

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Abstract

Effective cleaning and disinfection practices are essential in pig farming to prevent the spread of infectious agents. However, conventional detergents and disinfectants may leave residues that harbor microorganisms, pose toxicity risks to pigs, and negatively impact the environment. To address these concerns, this study investigated the use of a novel, non-chemical degradation technology based on light-emitting diode (LED) systems in the farrowing area of an enclosed, water-curtain-type specific pathogen-free (SPF) pig farm. New-generation hazardous-substance-reducing LED lights were installed in the facility, resulting in significant reductions in airborne bacterial counts and concentrations of harmful gases, including ammonia (NH_3) and ethylene (C_2H_4), as well as fine particulate matter ($PM_{2.5}$ and PM_{10}). Laboratory-based assays further confirmed that these LED systems effectively inhibited the replication of porcine reproductive and respiratory syndrome virus (PRRSV), highlighting their potential for disease prevention in swine production. Energy consumption analysis revealed that each 4-foot LED unit consumed only 15.8 W of electricity, in contrast to the 40 W consumed by the previously used fluorescent lights. With 54 LED units operating 9 hours daily, the annual energy saving was calculated to be 4,292.8 kWh. According to the latest national emission factor (0.494 kg CO_2e/kWh), this corresponds to an annual reduction of approximately 2.12 metric tons of carbon emissions. These findings demonstrate that hazardous-substance-reducing LED technology not only improves the hygienic and environmental conditions in pig farms but also contributes to energy conservation and carbon reduction goals. This innovation holds substantial potential for sustainable and net-zero carbon livestock farming.

Keywords: Antimicrobial efficacy; Atmospheric fine particulate matter; Degradation; Harmful substances; Light-emitting diode; Enclosed water-curtain-type specific pathogen-free pig farm

1. Introduction

The expansion of intensive pig farming has resulted in substantial environmental and public health challenges. Pig production systems generate large quantities of waste, leading to the release of various pollutants, including gaseous emissions, particulate matter, chemical residues, and microbial pathogens. Among these, ammonia (NH_3) derived from the decomposition of pig urine is of particular concern due to its contribution to air pollution, formation of secondary particulate matter, and adverse respiratory effects on both animals and humans. Methane (CH_4), a by-product of

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anaerobic manure decomposition, is a potent greenhouse gas that exacerbates climate change. Additionally, hydrogen sulfide (H_2S), emitted from pig manure, presents odor management challenges and poses toxicological risks at high concentrations [1-4].

Beyond gaseous emissions, pig farms are significant sources of particulate matter, which often contains allergens, pathogens, and chemical contaminants. The dispersion of these particles can negatively affect respiratory health and facilitate the spread of zoonotic diseases. Furthermore, nutrient-rich pig manure, when improperly managed, can contribute to eutrophication of aquatic ecosystems through nitrogen and phosphorus runoff. The presence of veterinary pharmaceuticals and heavy metals such as copper and zinc in pig waste also raises concerns regarding the development of antimicrobial resistance and soil contamination [5-8].

While conventional strategies such as improved ventilation and waste management practices have been employed to mitigate environmental impacts, there is a growing interest in exploring novel technologies for enhanced biosecurity and emission control. Visible light-emitting diodes (LED), particularly those emitting at wavelengths around 450 nm, have demonstrated antimicrobial properties without the cytotoxic effects commonly associated with ultraviolet light exposure. The antimicrobial action of visible light is largely attributed to the generation of reactive oxygen species (ROS), which can effectively inactivate a broad spectrum of pathogens. Recent observations have indicated that atmospheric oxidative conditions, particularly during periods of elevated temperature and high ozone (O_3) levels, may influence particulate matter dynamics. These findings suggest a potential interplay between oxidative environmental conditions and secondary pollutant formation, raising the possibility that antimicrobial LED technologies could contribute to environmental pollutant degradation [7-8]. This study aims to review the environmental impacts associated with the growing to finishing stages in an enclosed water-curtain-type SPF pig farm, examine the underlying mechanisms of antimicrobial LED action, and explore the potential for integrating LED-based technologies into livestock management systems to mitigate environmental and public health risks.

2. Materials and Methods

2.1. Experimental Animals and Conditions of an Enclosed Water-Curtain-Type SPF Pig Farm

The enclosed water-curtain-type specific pathogen-free (SPF) pig farm of the Agricultural Technology Research Institute (ATRI) is accredited with multiple certifications, including ISO 9001:2015 certification and ATRI SPF certification. SPF piglets are obtained through natural delivery from SPF-certified pregnant sows. All SPF animals are reared in biosecure barrier facilities that are free from major swine diseases. Importantly, no animal experiments involving zoonotic agents are permitted within these facilities. To ensure the health and welfare of the animals, strict personnel entry protocols are enforced. All staff must shower and change into cleanroom attire before entering the barrier facility. Depending on the biosafety level of the barrier, personnel are required to wear appropriate personal protective equipment (PPE), including dedicated clothing, shoes, gloves, masks, and caps, or full-body disposable suits. In addition, health checks and vaccinations are required for all personnel to minimize the risk of exposure to zoonotic pathogens and potential animal allergens. Environmental conditions within the SPF pig farms are strictly maintained, with a controlled temperature of 22-24 °C, relative humidity of 70%-75%, and a 12-hour light/12-hour dark photoperiod. All SPF pigs are provided ad libitum access to standard diets and fresh water. Prior to the commencement of any experimental procedures, animals undergo a one-week acclimation period. All animal procedures in this study were reviewed and approved by the Institutional Animal Care and Use Committee (IACUC) of ATRI. The experimental protocol (IACUC No. 111013) adhered strictly to the guidelines set forth by the IACUC ethics committee.

2.2. Development of Innovative Visible LED Technology and Its Application for Mitigating Harmful Substances in an Enclosed Water-Curtain-Type SPF Pig Farm

2.2.1. Anti-Microbial Efficacy after New-Generation LED Installation in an Enclosed Water-Curtain-Type SPF Pig Farm

A comprehensive analysis of microbial deposition was conducted within an enclosed, water-curtain-type specific pathogen-free (SPF) pig farm. Portable impact-type samplers were strategically positioned beneath pathway lighting, at the center of walkways, and beneath pig enclosures to collect airborne microbial samples. The collected samples were transported to the laboratory, where they were first exposed to LED light treatment for 8 hours. Following exposure, the samples were incubated in a culture chamber for 24 hours to promote microbial colony development. Statistical analysis was subsequently performed to assess colony growth and distribution.

2.2.2. Efficacy of Harmful Gas and Airborne Particulate Degradation after New-Generation LED Installation in an Enclosed Water-Curtain-Type SPF Pig Farm

Gas detectors and air quality monitors were strategically deployed at the center of the SPF pig farming area. These instruments continuously sampled ambient air to measure the concentrations of ammonia (NH_3), ethylene (C_2H_4), and particulate matter ($PM_{2.5}$ and PM_{10}). The primary objective was to quantify the levels of harmful gases and airborne particulates within the farm environment.

2.3. Application of the New-Generation LED for the Inhibition of PRRS Virus Replication

Additionally, the new-generation LED lighting with hazardous substance-reducing capabilities was tested for its inhibitory effect on PRRS virus. PRRS viral solution was poured into culture dishes and placed on ice, then exposed to either the novel LED or a regular LED light source for 1 hour. The exposed viral solutions were then co-cultured with MARC-145 cells at 37°C and 5% CO_2 for three days. The PRRS viral load was measured via qPCR to determine the C_t values.

2.4. Statistical Analysis

The data were expressed as mean ± SD (standard deviation). All comparisons were made by one-way ANOVA and all significant differences are reported at $^*p < 0.05$.

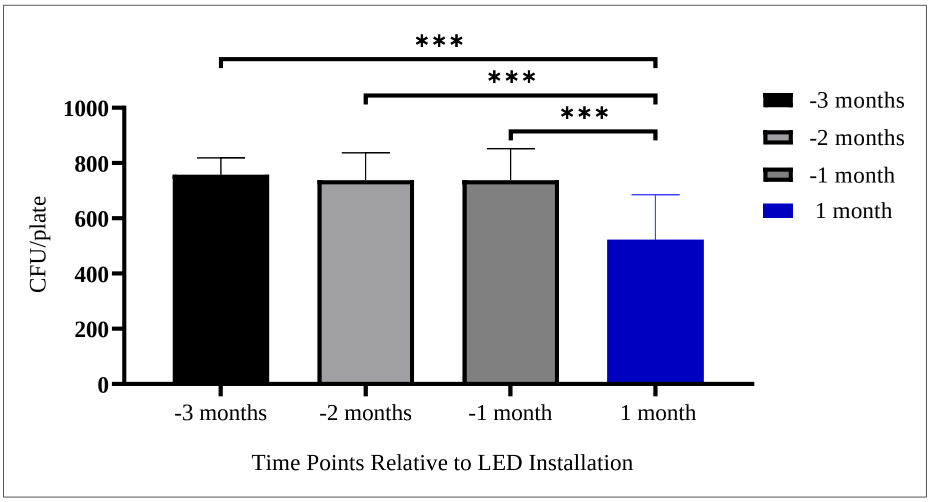
3. Results

3.1. Application of LED for Antimicrobial Efficacy During the Growing to Finishing Stages in an Enclosed Water-Curtain-Type SPF Pig Farm

In this study, baseline data were first collected over a three-month period before the installation of the lighting fixtures, including monthly measurements of airborne bacteria (settle plates), hazardous gases, and fine particulate matter (PM) in the air. Subsequently, after the installation of the novel light-emitting diode (LED) fixtures in the pig housing (Figure 1), additional sampling and testing were conducted to assess the number of airborne bacteria, levels of hazardous gases, and fine particulate matter. The collected data were subjected to statistical analysis to evaluate the efficacy of the novel LED lighting in purifying the pig housing environment.

Figure 1 Application of LED-based degradation technology for harmful substances during the growing to finishing stages in an enclosed water-curtain-type SPF pig farm. (A) Before the new-generation LED installation. (B) After the new-generation LED installation

During the three months prior to the installation of the LED fixtures, the average monthly colony-forming units (CFU) from the airborne bacteria tests were 757.8 ± 61 CFU, 737.8 ± 99.4 CFU, and 738.1 ± 113.6 CFU, respectively. After the installation, the average CFU dropped to 523.1 ± 162.1 CFU, indicating an average antibacterial reduction rate of 29.7% (Figure 2).



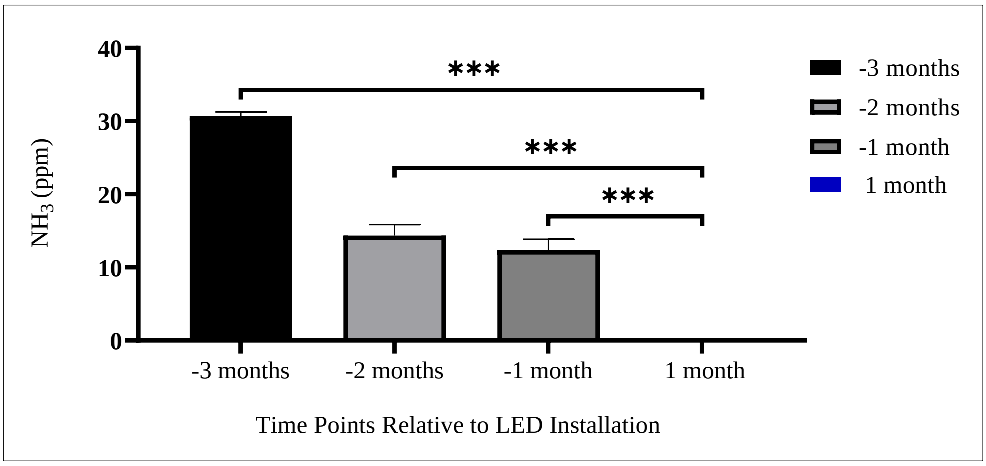
All data are expressed as mean ± SD. The significant differences are reported at ***$p < 0.001$

Figure 2 Assessment of microbial presence in the animal housing facility. Microbial counts were evaluated before 3 months- and after 1 month-this new-generation LED installation

3.2. Application of LED for Harmful gases and $PM_{2.5}$ and PM_{10} Degradation

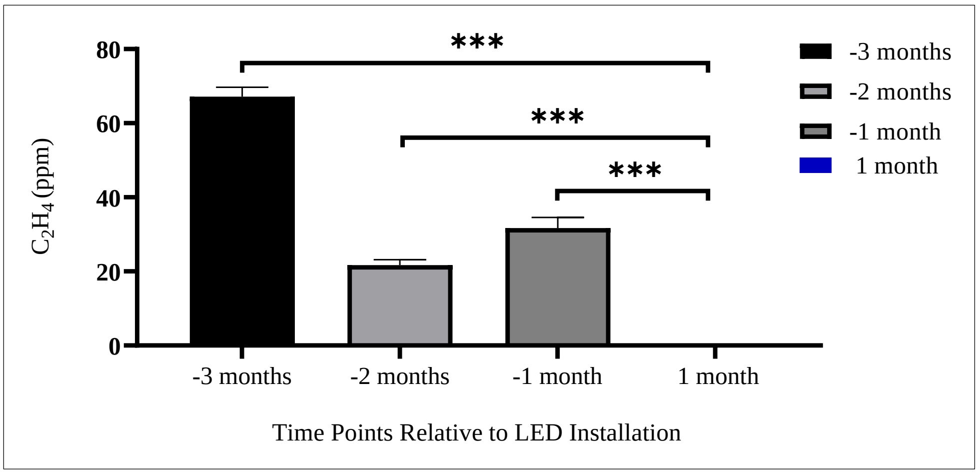
For the hazardous gas ammonia (NH_3), the monthly test results for the three months prior to installation were 30.6 ± 0.5 ppm, 14.3 ± 1.5 ppm, and 12.3 ± 1.5 ppm. After installation, levels were below the detection limit of the instrument (1 ppm), thus undetectable. This indicates an average NH_3 degradation rate of 100% post-installation (Figure 3). For ethylene (C_2H_4), the pre-installation values were 67.1 ± 2.5 ppm, 21.6 ± 1.5 ppm, and 31.6 ± 2.8 ppm. Post-installation, values were also below the detection limit, indicating a 100% degradation rate (Figure 4).

Regarding fine particulate matter, $PM_{2.5}$ concentrations during the three months prior to installation were 14.6 ± 2.0 μg/m^3, 14.3 ± 0.5 μg/m^3, and 9.6 ± 0.5 μg/m^3. After installation, the concentration was 5.3 ± 0.5 μg/m^3, showing a reduction rate of 58.6% (Figure 5). For PM_{10}, the values were 16.6 ± 2.0 μg/m^3, 16.3 ± 0.5 μg/m^3, and 10.6 ± 0.5 μg/m^3 prior to installation, and 5.3 ± 0.5 μg/m^3 post-installation, indicating a 63.4% reduction rate (Figure 6).



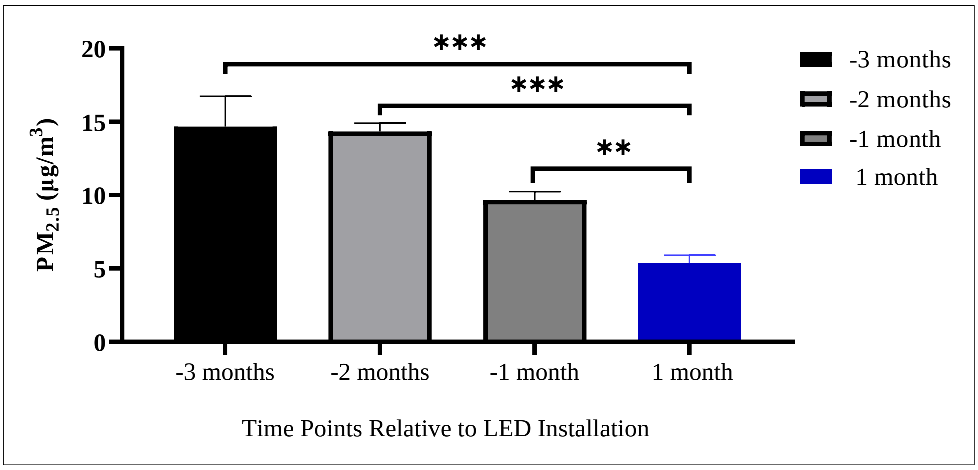
All values are presented as mean ± SD. A significance level of ***$p < 0.001$ was considered statistically significant.

Figure 3 The NH_3 concentration was measured before 3 months- and after 1 month-this new-generation LED installation



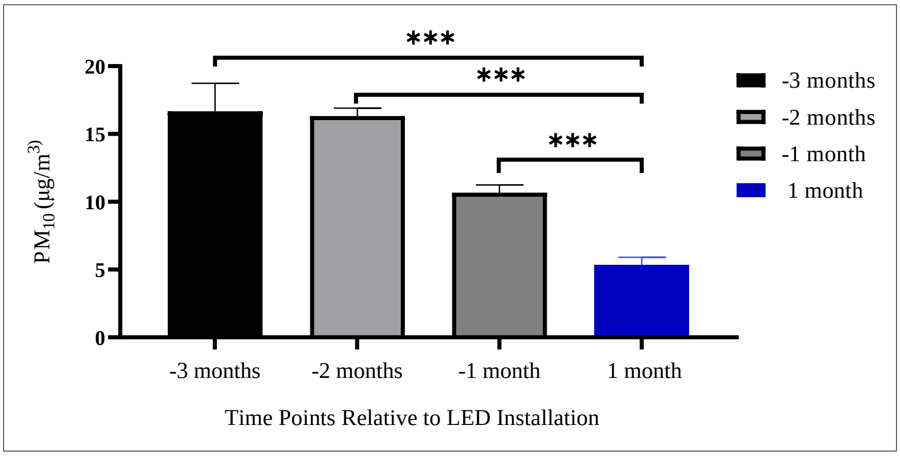
All values are presented as mean ± SD. A significance level of $^{***}p < 0.001$ was considered statistically significant

Figure 4 The C_2H_4 concentration was measured before 3 months- and after 1 month-this new-generation LED installation



All values are presented as mean ± SD. A significance level of $^{**}p < 0.01$ and $^{***}p < 0.001$ were considered statistically significant

Figure 5 The airborne particulate matter 2.5 concentration was measured before 3 months- and after 1 month-this new-generation LED installation

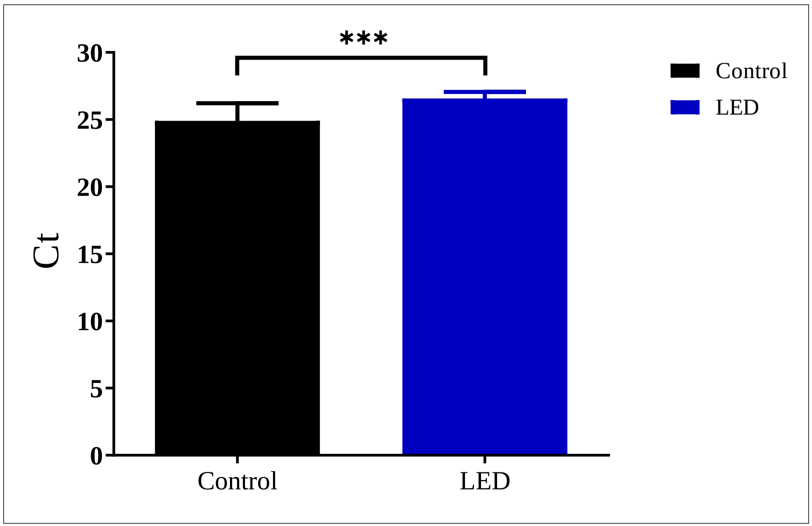


All values are presented as mean ± SD. A significance level of $^{***}p < 0.001$ were considered statistically significant

Figure 6 The airborne particulate matter 10 concentration was measured before 3 months- and after 1 month-this new-generation LED installation

3.3. Application of the New-Generation LED for the Inhibition of PRRS Virus Replication

The inhibitory effect of the new-generation LED lighting, designed to reduce hazardous substances, was evaluated against the porcine reproductive and respiratory syndrome (PRRS) virus. Results demonstrated that the viral load following exposure to the new-generation LED was significantly lower compared to that observed with traditional LED lighting (Figure 7). All experiments were performed within a biosafety cabinet to ensure operational safety and environmental control. The use of the biosafety cabinet effectively prevented external contamination and provided a stable environment for handling virus samples and LED devices, thereby protecting laboratory personnel and ensuring consistent experimental conditions.



All data are expressed as mean ± SD. The significant differences are reported at ***$p < 0.001$

Figure 7 New-generation LED installation for its inhibitory effect on PRRS virus.

4. Discussion

As the scale and intensification of livestock farming continue to grow in our domestic industry, there has been a concurrent rise in the concentration of harmful substances within animal shelters. These include gases, fine particulate matter, and pathogens, with their prevalence closely correlated to the expansion of farming operations [2-3]. Consequently, there is an urgent need to develop innovative and modular technologies tailored to the specific environmental conditions of pig farming in our country.

The harmful gases present in pig farming environments-defined as those that negatively impact livestock health and productivity as well as the well-being of farm workers-typically include $PM_{2.5}$, PM_{10}, ammonia (NH_3), hydrogen sulfide (H_2S), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and odors from fecal decomposition. These gases predominantly originate from animal respiration, manure breakdown, and feed decomposition. Elevated concentrations can seriously compromise animal welfare and, if left unaddressed, may lead to poisoning or death. Common environmental monitoring parameters for animal shelters include $PM_{2.5}$ levels, concentrations of NH_3 and H_2S, and oxygen availability. Utilizing specialized instruments to detect whether harmful gas concentrations exceed safety thresholds remains an effective strategy for maintaining optimal shelter conditions [7-8].

In our previous publication [9], we demonstrated that a 450 nm wavelength LED device exerted significant cytotoxic effects on HT-29 and CT-26 colon cancer cell lines in vitro and substantially inhibited tumor growth in CT-26-bearing mice in vivo. Furthermore, we reported that the same 450 nm LED device exhibited strong antibacterial activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa*, as well as the capacity to degrade airborne fine particulate matter ($PM_{2.5}$) under laboratory conditions [7-8, 10-12]. These findings marked the first demonstration of the new-generation LED technology achieving both $PM_{2.5}$ degradation and antimicrobial functionality.

Building upon these achievements, we extended our investigation to pig farming environments to assess the practical application of our new-generation LED devices. Experimental studies were conducted at both an open-type SPF pig farm and a conventional pig farm. In the open-type SPF facility, after 8 hours of the new-generation LED exposure, the antimicrobial efficacy ranged from 34.87% to 91.63%, with effectiveness dependent on the height of the light source. Ammonia degradation ranged from 8.98% to 9.58%, with efficacy improving alongside longer exposure durations. In the conventional pig farm, our new-generation LED devices demonstrated significant reductions in $PM_{2.5}$ and PM_{10} concentrations, with degradation rates ranging from 8.89% to 86.67% for $PM_{2.5}$ and from 12.5% to 85.0% for PM_{10}, also showing a clear dependence on exposure duration. Antimicrobial efficacy in this setting ranged from 11.58% to 13.33% after 8 hours of exposure, with no apparent correlation to the height of the light source [10-12]. Based on these results, we successfully developed an advanced LED module featuring three core functions: degradation of $PM_{2.5}$/PM_{10}, reduction of harmful gases, and potent antimicrobial activity. This innovative technology presents a highly effective tool for environmental purification and disinfection in pig farming operations, with the potential to reduce disease incidence and minimize economic losses [10-12].

In this study, statistical analysis confirmed that the installation of the new-generation LED during the growing to finishing stages in an enclosed water-curtain-type SPF pig farm significantly reduced microbial deposition and $PM_{2.5/10}$ levels. Moreover, harmful gases as NH_3 detectable before the new-generation LED installation became undetectable afterward, indicating effective environmental remediation. Together, results from microbial deposition tests, harmful gas degradation assessments, antibacterial efficacy evaluations, and airborne particulate reduction studies validate the establishment of a comprehensive harmful substance monitoring and mitigation system. At present, the new-generation LED technology developed by ATRI has demonstrated promising initial results in mitigating harmful substances within SPF and conventional pig farming facilities. This advancement holds great potential for widespread adoption across the livestock sector, contributing to improved farm hygiene, enhanced animal health, and sustainable agricultural development.

On the other hand, most purification lights on the market are ultraviolet lights, which, although effective in inhibiting bacterial growth, are harmful to humans and have a limited irradiation range. The new-generation LED lights with hazardous substance-reducing capabilities utilize surface photo-plasma technology, where light-driven quantum effects cause water molecules to vibrate and produce ions and free electrons. These ions decompose harmful substances in the air into inert compounds. This technology not only effectively degrades hazardous substances but is also harmless to living organisms, offers a wider illumination range, is more energy-efficient, and provides brighter lighting [7-8, 10-12]. When comparing the power consumption of the new-generation LED lights to traditional fluorescent lights, the 4-foot hazardous-substance-reducing LED light used in this study consumes 15.8W, whereas the original fluorescent lights used in the pig farm were 40W. A total of 54 the new-generation LED lights were installed in the facility. Assuming the lights are used 9 hours per day, this translates to an annual saving of 4,292.8 kWh of electricity. Based on the latest emission factor of 0.494 (announced by the Ministry of Economic Affairs), this would reduce carbon emissions by approximately 2.12 metric tons per year. Therefore, the low power consumption of these new-generation LED lights can help reduce carbon emissions and play a key role in achieving net-zero carbon goals.

5. Conclusion

In summary, the installation of the new-generation LED with hazardous substance-reducing capabilities during the growing to finishing stages in an enclosed water-curtain-type SPF pig farm significantly reduced airborne bacteria counts, degraded harmful gases (NH_3 and C_2H_4), and decreased fine particulate matter ($PM_{2.5}$ and PM_{10}). Laboratory experiments also confirmed that this new-generation LED lights significantly inhibited PRRSV replication. Additionally, after the new-generation LED installation in an enclosed water-curtain-type SPF pig farm, this would reduce carbon emissions by approximately 2.12 metric tons per year. Therefore, the new-generation LED installation can help reduce carbon emissions and play a key role in achieving net-zero carbon goals.

Looking ahead, we will plan to integrate advanced visible LED technology with an automated harmful substance monitoring system to develop a real-time environmental monitoring and purification platform for animal housing facilities. This system will be capable of continuously detecting harmful factors such as gases, airborne particulate matter, and pathogens within the housing environment [13-14]. Based on the collected data, the system will automatically activate the new-generation LED technology to degrade these harmful components in real time. The ultimate goal is to improve animal welfare, safeguard the health and safety of personnel, and reduce potential economic losses in the livestock industry through simultaneous environmental purification and real-time monitoring.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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