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(Research Article)

Application of light-based environmental remediation technology to reduce harmful substances in a traditional nursery pig farm

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Abstract

Effective environmental sanitation is essential for limiting pathogen transmission and maintaining animal and worker health in pig production facilities. However, conventional chemical cleaning and disinfection practices may generate residues and impose additional environmental burdens. This study evaluated a novel, non-chemical environmental remediation system based on light-emitting diode (LED) technology during the nursery stage at a traditional pig farm. Following installation of the new-generation hazardous-substance-reducing LED fixtures, airborne bacterial counts decreased by 28.5%. Concentrations of ammonia (NH_3), ethylene (C_2H_4), $PM_{2.5}$, and PM_{10} decreased by 85.5%, 45.8%, 59.3%, and 47.4%, respectively. Each 4-foot LED fixture consumed 15.8 W, compared with 40 W for the fluorescent fixture previously used. For 32 fixtures operated for 12 h/day, the estimated annual electricity saving was 2,214.528 kWh. Using an electricity emission factor of 0.474 kg CO_2e/kWh, this saving corresponds to an estimated annual reduction of approximately 1.6077 metric tons of CO_2e. These findings indicate that the LED system can improve air quality and microbial control in nursery pig housing while simultaneously reducing energy consumption and associated carbon emissions. The technology therefore represents a promising approach for improving environmental management and supporting low-carbon livestock production.

Keywords: Airborne Bacteria; Ammonia; Environmental Remediation; Light-Emitting Diode; Particulate Matter; Pig Housing

1. Introduction

The intensification of pig production has created substantial environmental and public-health challenges. Pig housing systems generate gaseous emissions, particulate matter, chemical residues, and microbial contaminants. Ammonia (NH_3), primarily produced through the decomposition of nitrogenous compounds in urine and manure, contributes to poor air quality, secondary particulate formation, and adverse respiratory effects in both pigs and farm workers. Methane (CH_4), generated during anaerobic manure decomposition, is an important greenhouse gas, whereas hydrogen sulfide (H_2S) contributes to odor problems and can be toxic at elevated concentrations [1-4].

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Pig farms are also important sources of airborne particulate matter, which may carry allergens, microorganisms, and chemical contaminants. These particles can impair respiratory health and facilitate the dissemination of infectious agents. In addition, improper manure management may contribute to eutrophication through nitrogen and phosphorus runoff. Veterinary drug residues and heavy metals, including copper and zinc, may further promote antimicrobial resistance and soil contamination [5-8].

Conventional mitigation strategies include ventilation, manure management, and chemical cleaning and disinfection. Nevertheless, there is increasing interest in non-chemical technologies that can strengthen biosecurity while reducing airborne pollutants. Visible-light LED systems, particularly those operating near 450 nm, have demonstrated antimicrobial activity and avoid the direct hazards associated with ultraviolet irradiation. Their antimicrobial effects are generally attributed to photo-induced oxidative processes and the generation of reactive oxygen species, which can damage microbial cellular components. Oxidative atmospheric conditions may also influence particulate and gaseous pollutant dynamics, suggesting that appropriately designed LED systems could contribute to environmental remediation [7,8]. Accordingly, this study evaluated the practical effects of a new-generation LED system on airborne bacterial counts, harmful-gas concentrations, particulate matter, electricity consumption, and associated carbon emissions during the nursery stage in a traditional pig farm.

2. Material and methods

2.1. Animals and Housing Conditions at the Traditional Pig Farm

The study was conducted at a traditional pig farm operated by the Agricultural Technology Research Institute (ATRI). Pigs were housed in biosecure facilities maintained free of major swine diseases, and experiments involving zoonotic agents were not permitted. Personnel followed strict entry procedures and wore appropriate personal protective equipment, including dedicated clothing, footwear, gloves, masks, and caps or disposable coveralls. Routine health surveillance and vaccination requirements were implemented to reduce risks associated with zoonotic pathogens and animal allergens. Housing temperature and relative humidity were controlled, and a 12-h light/12-h dark photoperiod was maintained. Pigs had ad libitum access to a standard diet and fresh water and were allowed to acclimate for one week before data collection. All procedures were reviewed and approved by the ATRI Institutional Animal Care and Use Committee (IACUC No. 113085) and were conducted in accordance with institutional animal-care guidelines.

2.2. Application of the New-Generation Visible-Light LED System in a Traditional Nursery Pig Farm

2.2.1. Assessment of Airborne Bacterial Counts

Airborne microbial contamination was assessed at multiple representative locations within the nursery facility, including areas beneath aisle lighting, at the center of walkways, and near pig pens. Airborne microorganisms were collected using portable impact-type air samplers. Samples were transported to the laboratory and cultured under standardized conditions for 24 h to permit colony development. Colony-forming units (CFU) were then counted and used to compare microbial contamination before and after installation of the LED system.

2.2.2. Measurement of Harmful Gases and Airborne Particulate Matter

Gas detectors and air-quality monitors were positioned at the center of the nursery housing area. Ambient air was sampled to determine the concentrations of ammonia (NH_3), ethylene (C_2H_4), $PM_{2.5}$, and PM_{10}. Measurements were obtained monthly for three months before LED installation and again one month after installation.

2.3. Statistical Analysis

Data are presented as the mean ± standard deviation (SD). Group differences were analyzed using one-way analysis of variance (ANOVA). A value of $p < 0.05$ was considered statistically significant.

3. Results

3.1. Reduction in Airborne Bacterial Counts after LED Installation

Baseline measurements were collected monthly for three months before installation of the LED fixtures. Airborne bacterial counts, harmful-gas concentrations, and airborne particulate matter were then measured again one month after installation (Figure 1). These data were analyzed to evaluate changes in the nursery-house environment associated with operation of the new-generation LED system.

Figure 1 Application of the new-generation LED environmental remediation system in a traditional nursery pig farm. (A) Facility before LED installation. (B) Facility after LED installation.

Mean airborne bacterial counts during the three months before LED installation were 775.7 ± 34.8, 724.9 ± 29.2, and 744.6 ± 26.3 CFU/plate, respectively. One month after installation, the mean count decreased to 535.4 ± 28.5 CFU/plate, corresponding to a 28.5% reduction relative to the mean pre-installation value (Figure 2).

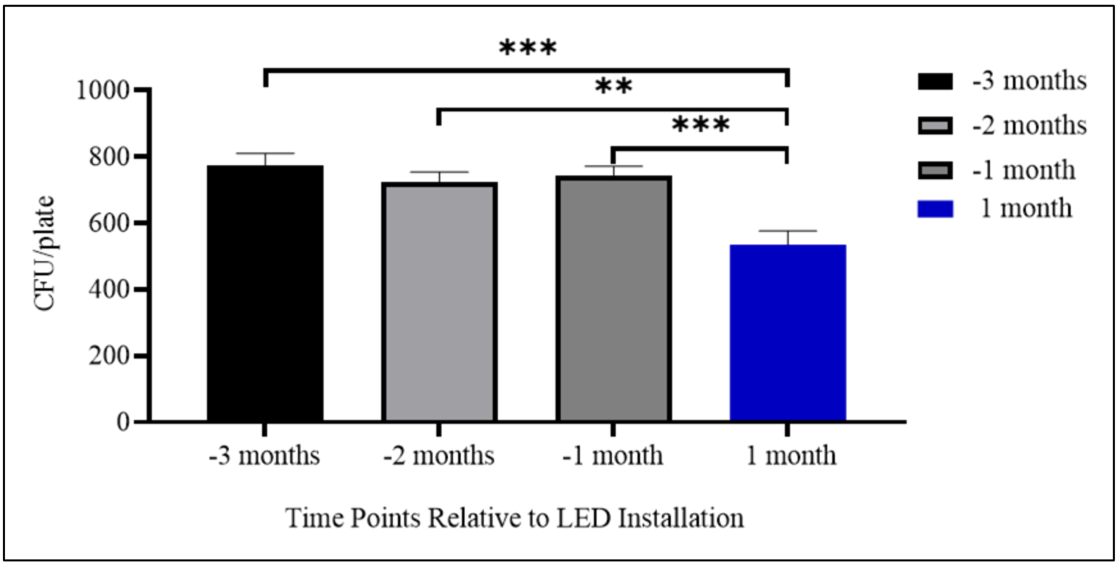

Figure 2 Airborne bacterial counts measured during the three months before and one month after installation of the new-generation LED system. Data are presented as the mean ± SD. $^{**}p < 0.01$; $^{***}p < 0.001$.

3.2. Reductions in Harmful Gases and Airborne Particulate Matter after LED Installation

Mean NH_3 concentrations during the three months before LED installation were 34.4 ± 13.5, 28.0 ± 6.4, and 30.9 ± 12.3 ppm, respectively. One month after installation, the NH_3 concentration decreased to 4.5 ± 0.5 ppm, representing an 85.5% reduction relative to the mean pre-installation concentration (Figure 3). Mean C_2H_4 concentrations before installation were 2.5 ± 0.7, 2.4 ± 0.3, and 2.3 ± 0.3 ppm; after installation, the concentration decreased to 1.3 ± 0.3 ppm, corresponding to a 45.8% reduction (Figure 4).

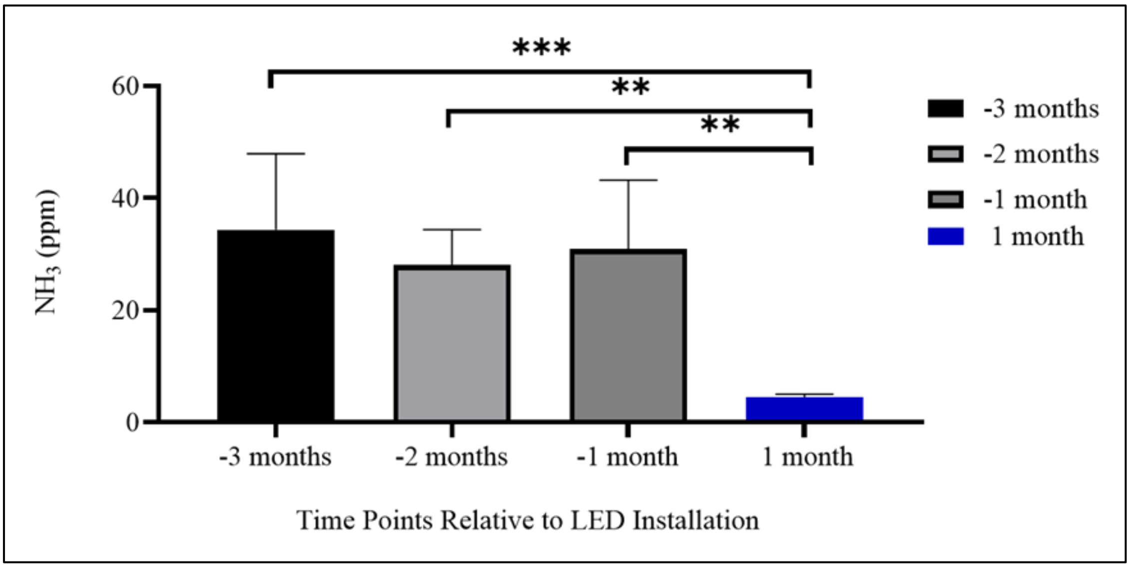

Figure 3 Ammonia (NH_3) concentrations measured during the three months before and one month after installation of the new-generation LED system. Data are presented as the mean ± SD. $^{**}p < 0.01$; $^{***}p < 0.001$.

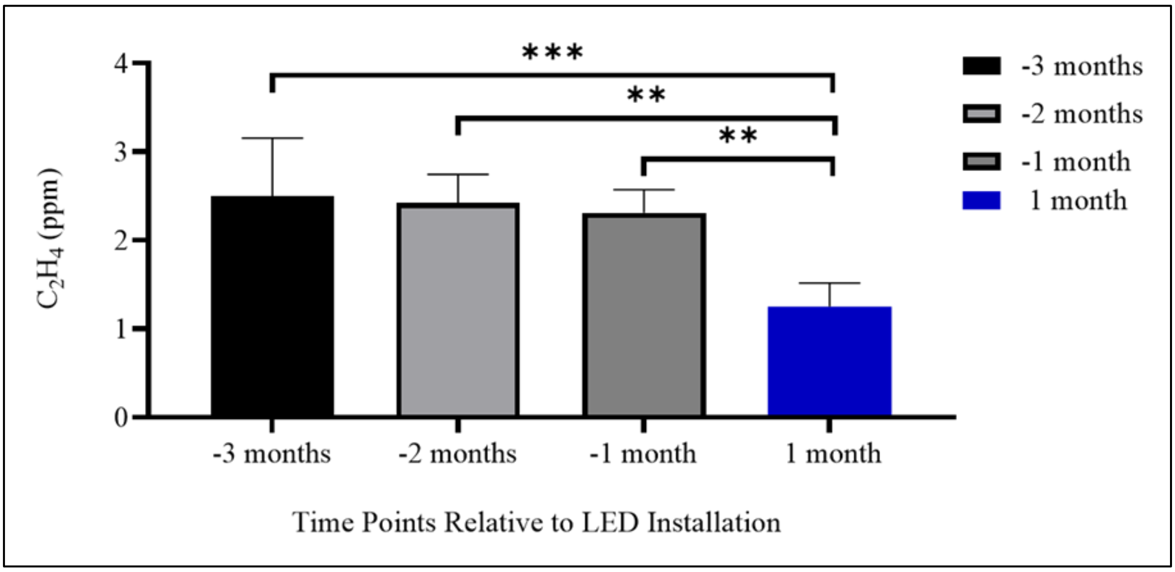

Figure 4 Ethylene (C_2H_4) concentrations measured during the three months before and one month after installation of the new-generation LED system. Data are presented as the mean ± SD. $^{**}p < 0.01$; $^{***}p < 0.001$.

Mean $PM_{2.5}$ concentrations during the three months before installation were 12.6 ± 0.5, 13.4 ± 0.5, and 13.1 ± 0.8 μg/m^3, respectively. One month after installation, the concentration decreased to 5.3 ± 0.5 μg/m^3, corresponding to a 59.3% reduction (Figure 5). Mean PM_{10} concentrations before installation were 13.5 ± 1.7, 13.9 ± 0.6, and 13.1 ± 0.8 μg/m^3; after installation, the concentration decreased to 7.1 ± 0.8 μg/m^3, representing a 47.4% reduction (Figure 6).

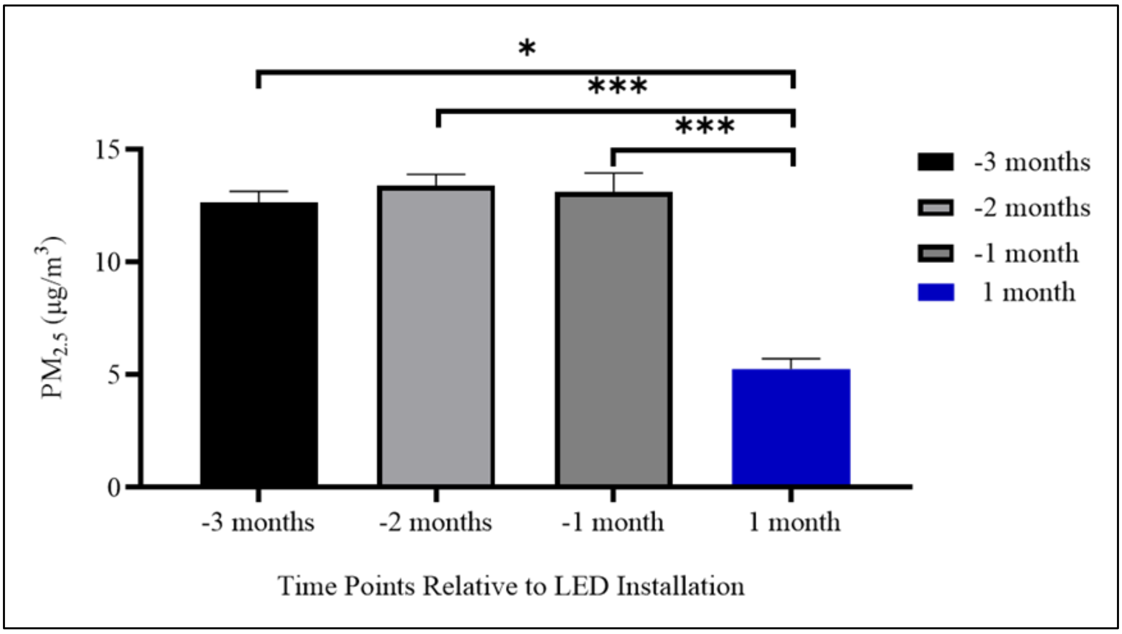

Figure 5 $PM_{2.5}$ concentrations measured during the three months before and one month after installation of the new-generation LED system. Data are presented as the mean ± SD. $^*p < 0.05$; $^{***}p < 0.001$.

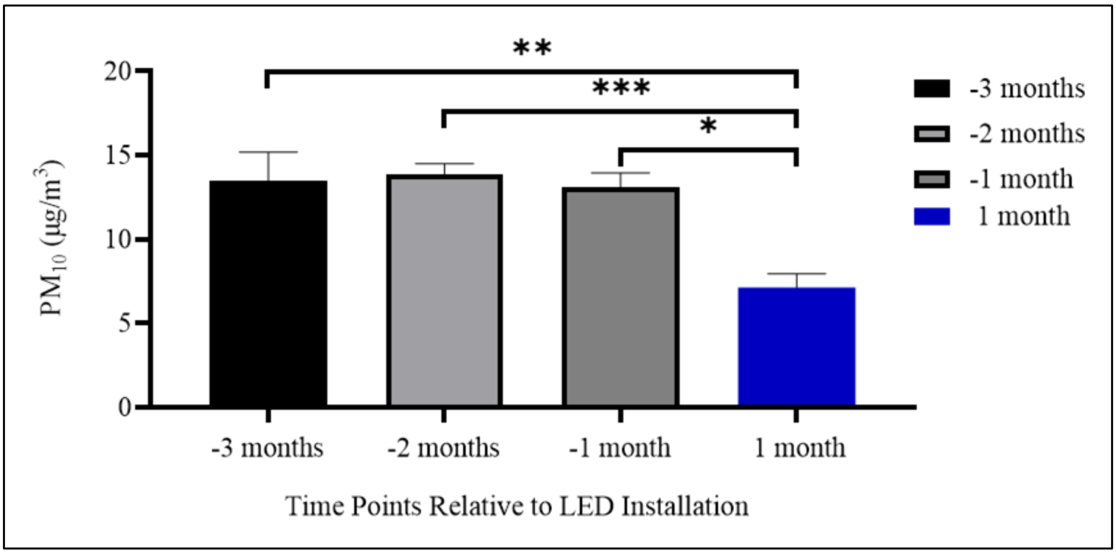

Figure 6 PM_{10} concentrations measured during the three months before and one month after installation of the new-generation LED system. Data are presented as the mean ± SD. $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

4. Discussion

Increasing production intensity can elevate concentrations of airborne microorganisms, particulate matter, and harmful gases in livestock housing. Consequently, practical environmental-control technologies that can be integrated into existing pig facilities are needed. The present field study demonstrates that installation of a new-generation visible-light LED system was associated with substantial improvements in several indicators of nursery-house air quality.

Airborne contaminants in pig housing arise from animal respiration, manure and urine decomposition, feed, bedding, and routine animal activity. Important monitoring targets include NH_3, H_2S, CO_2, CH_4, particulate matter, and bioaerosols. At elevated concentrations, these contaminants can impair respiratory health, reduce productivity, compromise animal welfare, and increase occupational exposure among farm workers. Continuous or periodic environmental monitoring is therefore essential for identifying conditions that exceed recommended limits and for evaluating the effectiveness of mitigation measures [7,8].

Our previous studies showed that a 450-nm LED device exerted phototoxic effects on colon cancer cell lines and inhibited tumor growth in a mouse model [9]. The same LED platform also demonstrated antibacterial activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa* and reduced airborne $PM_{2.5}$ under laboratory conditions [7,8,10-12]. These findings provided the basis for evaluating the technology under commercial livestock-production conditions.

Earlier field evaluations conducted in open-type specific-pathogen-free and traditional pig farms indicated that LED performance varied with installation height and exposure duration. Reported antimicrobial efficacy ranged from 34.87% to 91.63% in an open-type facility, while ammonia reduction ranged from 8.98% to 9.58%. In a traditional pig farm, $PM_{2.5}$ and PM_{10} reductions ranged from 8.89% to 86.67% and from 12.5% to 85.0%, respectively, and antimicrobial efficacy after 8 h of exposure ranged from 11.58% to 13.33% [10-12]. Collectively, these studies supported development of an LED module intended to provide three complementary functions: microbial control, reduction of harmful gases, and reduction of airborne particulate matter.

In the present study, airborne bacterial counts decreased by 28.5% after LED installation. NH_3 and C_2H_4 concentrations decreased by 85.5% and 45.8%, respectively, while $PM_{2.5}$ and PM_{10} concentrations decreased by 59.3% and 47.4%. These results indicate that the system can improve multiple environmental parameters simultaneously in a traditional nursery pig facility. However, because the study used a before-and-after field design without a concurrent untreated control house, the observed changes should be interpreted as associations with LED installation rather than definitive evidence that all reductions were caused exclusively by the LED system. Seasonal conditions, ventilation, stocking density, manure management, and other farm-level factors may also have contributed. Future studies should incorporate concurrent control facilities, longer follow-up periods, repeated seasonal measurements, and direct monitoring of animal-health and production outcomes.

Most commercially available germicidal lighting systems rely on ultraviolet radiation, which requires strict exposure controls because of potential risks to animals and personnel. The visible-light LED system evaluated here is designed to operate in occupied environments and uses a surface photo-plasma process intended to generate reactive ions and electrons that interact with airborne contaminants [7,8,10-12]. In addition to its environmental-control functions, the system consumed substantially less electricity than the fluorescent lighting it replaced. Each 4-foot LED fixture consumed 15.8 W compared with 40 W for the original fluorescent fixture. For 32 fixtures operated for 12 h/day, the estimated annual electricity saving was 2,214.528 kWh. Applying an electricity emission factor of 0.474 kg CO_2e/kWh yields an estimated annual reduction of approximately 1.6077 metric tons of CO_2e. Thus, replacing conventional lighting with this LED system may provide both environmental and energy-efficiency benefits.

5. Conclusion

Installation of the new-generation visible-light LED system in a traditional nursery pig farm was associated with lower airborne bacterial counts and reduced concentrations of NH_3, C_2H_4, $PM_{2.5}$, and PM_{10}. The system also consumed less electricity than the fluorescent lighting it replaced, corresponding to an estimated annual saving of 2,214.528 kWh and a reduction of approximately 1.6077 metric tons of CO_2e. These findings support the potential of LED-based environmental remediation as a practical component of low-carbon and health-oriented livestock housing management.

Future work should integrate the LED system with automated environmental sensors to establish a real-time monitoring and response platform for animal housing. Such a system could continuously track gaseous pollutants, airborne particulate matter, and microbial indicators and adjust LED operation according to predefined environmental thresholds [13-16]. Validation in controlled, multi-farm studies will be necessary to determine long-term effectiveness, optimize operating conditions, and assess effects on animal health, worker exposure, productivity, and economic performance.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that they have no conflicts of interest.

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