GSC Biological and Pharmaceutical Sciences

eISSN: 2581-3250 CODEN (USA): GBPSC2

Cross Ref DOI: 10.30574/gscbps

Journal homepage: https://gsconlinepress.com/journals/gscbps/

(Research Article)

Check for updates

Application of new-generation light-emitting diode technology for degradation of harmful substances in environmental control of traditional meat stalls and meat shops

Yu-Hsing Lin [1, #], Ya-Ling Cyue [2, #], Keng-Chia Hsu [2], Pi-Hsin Chen [2], Shih-Yi Guo [2], Ya-Peng Wang [2], Tsung-Han Wu [2], Chia-Ying Lin [2], Jhih-Yun Wang [2], Shao-Qun Lai [3] and Shao-Wen Hung [2, 4, *]

[1] *Department of Pet Healthcare, Yuanpei University of Medical Technology, Hsinchu 300, Taiwan.*

[2] *Division of Animal Industry, Animal Technology Research Center, Agricultural Technology Research Institute, Miaoli 350, Taiwan.*

[3] *Division of Animal Resources, Animal Technology Research Center, Agricultural Technology Research Institute, Miaoli 350, Taiwan.*

[4] *Department of Nursing, Yuanpei University of Medical Technology, Hsinchu 300, Taiwan.*

[#] *Contributed equally to this work*

GSC Biological and Pharmaceutical Sciences, 2025, 31(01), 256-267

Publication history: Received on 06 March 2025; revised on 17 April 2025; accepted on 19 April 2025

Article DOI: https://doi.org/10.30574/gscbps.2025.31.1.0156

Abstract

Microbial contamination of meat products poses a persistent threat to global food safety and public health. In Taiwan, fresh pork is commonly sold at ambient temperatures in traditional markets, increasing the risk of spoilage and microbial proliferation. This study investigates the effectiveness of newly developed light-emitting diode (LED) technology in improving the environmental hygiene of meat retail settings. These new-generation LED technology is engineered for multifunctional environmental control, including antimicrobial activity and the degradation of harmful substances. Field tests were conducted at various pork retail sites to evaluate the impact of LED installation on environmental parameters. Results were demonstrated significant reductions in bacterial counts and concentrations of ethylene (C_2H_4) and ammonia (NH_3), while methane (CH_4) and hydrogen sulfide (H_2S) were undetectable before and after installation. Additionally, formaldehyde (CH_2O) and total volatile organic compounds (TVOCs) exhibited notable decreases. Anti-microbial efficacy rates ranged from 24.1% to 81.0% across different fields. In cold storage rooms of the test fields, the levels of airborne particulate matter ($PM_{2.5}$ and PM_{10}) also significantly declined. These findings suggest that integrating advanced LED technologies in traditional meat retail environments can effectively reduce microbial and chemical hazards, enhance food safety, and support the modernization of the meat industry.

Keywords: Light-Emitting Diode; Degradation of Harmful Substances; Traditional Meat Stalls; Meat Shops

1. Introduction

Microbial contamination of food is a major global public health concern. Over the years, incidents of food poisoning caused by microbial contamination have led to numerous product recalls, particularly involving meat products that triggered outbreaks of severe diseases. The term "meat" refers to flesh, skeletal muscle, and any attached connective tissues or fat, but excludes bones and bone marrow. Meat is a good source of protein, essential fatty acids, minerals, and vitamins. However, due to its nutrient-rich composition, it is highly perishable and offers an ideal medium for microbial growth [1-2].

* Corresponding author: Shao-Wen Hung

Although healthy animal muscle contains few or no microbes, contamination can occur during slaughter and transportation. During bleeding, handling, and processing, meat can easily become contaminated by external sources through knives, tools, clothing, hands, and the air. Contaminated meat and meat products are susceptible to a range of biological, chemical, and physical hazards-especially microbial. The degree of microbial contamination and the composition of microbial flora are indicators of meat hygiene [3-5].

Foodborne pathogens are a leading cause of disease and death in developing countries, with an estimated 1.4 million cases caused by non-typhoidal *Salmonella* serotypes and 270,000 cases by pathogenic *Escherichia coli*, including *E. coli* O157:H7. While these pathogens often cause self-limiting gastroenteritis, they may also lead to invasive diseases and complications. Systemic *Salmonella* infections can be life-threatening, and Shiga-toxin-producing *E. coli*, especially *E. coli* O157:H7, can cause bloody diarrhea and hemolytic uremic syndrome (HUS). There is growing awareness of the public health impact of zoonotic foodborne pathogens transmitted from animal-derived foods [6-10].

Key foodborne bacterial pathogens associated with meat include *Salmonella*, *Staphylococcus aureus*, *E. coli*, *Campylobacter jejuni*, *Listeria monocytogenes*, *Clostridium perfringens*, *Yersinia enterocolitica*, and *Aeromonas hydrophila*. Among these, *Salmonella*, *Campylobacter*, *Listeria*, and toxigenic *E. coli* O157 are of particular public health concern. *Pseudomonas* species are associated with meat spoilage, causing unpleasant odors, discoloration, and gas formation. *Vibrio* species also pose a risk, causing gastroenteritis, wound infections, and septicemia. Therefore, this study aims to apply new-generation light-emitting diode (LED) technology to degrade harmful substances and improve environmental control in traditional meat stalls and meat retail shops to ensure food safety. [11-15]

The global food safety testing market is growing due to several factors: increasing incidence of foodborne illnesses, tightening regulations in major countries, media attention, growing consumer awareness, globalization of the food supply chain, and rising demand for food safety testing in emerging markets such as China, India, and Southeast Asia. The rise of rapid detection technologies also contributes to this growth. In Taiwan, the average pork consumption is about 32 kg per person per year. The island's subtropical climate, especially the hot and humid months from June to September, is particularly unsuitable for selling meat at room temperature. Spoiled meat is defined as pork with 30 million bacteria per gram; in traditional markets, pork stored at room temperature can contain around 1 million bacteria per gram, doubling every 30 minutes. According to national standards, pork left at room temperature for more than 3 hours is considered spoiled. Temperature is the most critical factor affecting meat preservation, and Taiwan's high temperatures and humidity make current pork transportation processes a breeding ground for bacteria [1-2].

Most Taiwanese consumers prefer to buy freshly slaughtered warm pork from traditional markets. As a result, domestically produced fresh pork is primarily transported and sold at ambient temperatures. Around 70% of pork in Taiwan is sold as warm meat through traditional retail markets. Meat, rich in proteins, fats, and water, is an ideal medium for microbial growth. Taiwan's consistently hot and humid environment supports temperature-dependent microbial proliferation, making warm pork particularly susceptible to bacterial contamination and subsequent food safety risks [16].

According to surveys, Taiwan has about 8,000 traditional pork stalls. From 2017 to 2020, a total of 419 pork vendors applied for installing temperature-controlled cabinets. In 2022, the Council of Agriculture, together with the Ministry of Economic Affairs and local governments, promoted the use of temperature-controlled equipment among 3,000 vendors. Properly equipped stalls provide a better environment and, in light of rising food safety awareness, consumer demand is expected to push vendors to adopt chilled pork. If pork can be kept at approximately 18°C, it would align with consumer habits while enhancing food safety [16-17].

Based on the "2022 Guidelines for Subsidizing Temperature-Control Equipment for Traditional Meat Stalls and Transportation Vehicles," efforts have been made to modernize slaughterhouses and upgrade cold chain logistics, accelerating the installation of temperature-control equipment in traditional meat stalls and transport vehicles. This supports a complete temperature-controlled supply chain for domestic meat products. Subsidies cover stall refrigeration equipment, transportation vehicle cooling systems, and upgrades to market power capacities. Meat stall refrigeration must maintain 10-20°C, and carcass transport vehicles must maintain 0-5°C [17].

Having temperature control is clearly better than none. Pork is typically delivered to stalls between 3-4 AM when temperatures are lower, but daytime heat during sales hours poses a risk. Storing pork in refrigerated units during these times would be significantly better than leaving it at room temperature. Furthermore, modernizing meat sales is a growing trend and well accepted by consumers, who prefer fresh pork stored in temperature-controlled equipment for both freshness and safety [17].

Current disinfection methods fall into physical (e.g., washing, light, heating) and chemical categories. Chemical disinfectants include surfactants, acids, alkalis, halogens, oxidizers, alcohols, phenolics, dyes, heavy metals, formaldehydes, and broad-spectrum formulations. However, many traditional methods pose environmental risks. Research showed that deep ultraviolet light with a 222 nm wavelength has strong disinfection capability and is safe for mice, causing no skin cancer or eye damage. The UVB range (280-315 nm), on the other hand, did induce harmful effects [18-23].

Photocatalysts, which do not undergo chemical changes themselves but induce reactions under light exposure, can break down organic compounds and bacteria. The most commonly used photocatalyst is titanium dioxide (TiO_2), which requires UV light with wavelengths under 380 nm to activate. TiO_2 is favored for its strong redox potential, chemical stability, environmental safety, and low cost. The integration of biomedical and optoelectronic technologies is now a major global trend, especially for improving animal health management. With LED technology advancements, light sources originally used for illumination can now be adapted for applications such as sterilization and air purification through coating innovations and photocatalytic enhancements [16-17, 22-23].

As food safety is a global concern, the development and application of new-generation LED technology to degrade harmful substances in traditional meat stalls and retail environments is both necessary and promising. These technologies help extend shelf life, maintain freshness, and promote industry modernization, ultimately benefiting farmers by increasing product value and revenue

2. Material and methods

2.1. Fabrication of LED Fixtures

2.1.1. Fixture Fabrication

LED chips will be fabricated and subjected to preliminary antimicrobial activity testing. After packaging, the components will be integrated with circuits and ICs, followed by assembly onto carriers. Performance evaluations will include brightness, power consumption, and the efficacy of degrading harmful gases, fine particulate matter (PM), and suppressing pathogens.

2.1.2. Technology Development and Optimization

Different emission types of epitaxial layers will be selected for LED fabrication. Crystal processing will be incorporated into the diode manufacturing workflow to enhance the multi-functionality of LEDs. Subsequent steps include primary color chip packaging and testing for the degradation of harmful gases and PM, as well as the suppression of pathogenic microorganisms.

2.2. Bacterial Fallout Testing in Traditional Meat Stalls

A portable impactor air sampler with a 50% collection efficiency cut-off diameter ($D50 \leq 1$ μm) will be used for air sampling. At least two sampling points should be set at each site, with additional points added if necessary. The sampler must be placed on a platform at a height of approximately 120-150 cm above ground level and must not be handheld to avoid contamination by the sampler operator. A petri dish containing culture media will be placed inside the sampler, and a suitable volume of air will be drawn in to impact bioaerosol particles onto the culture medium. Sampling duration must not exceed 10 minutes to prevent microbial desiccation. After sampling, the lid of the petri dish should be wiped with 70%-75% alcohol before being sealed. Duplicate sampling is required for each location using two samplers simultaneously, spaced 30-40 cm apart. Samples should be delivered to the laboratory for incubation within 24 hours.

2.3. Evaluation of LED Efficacy in Degrading Harmful Gases in Traditional Meat Stalls

LED fixtures will be used to evaluate their effectiveness in degrading harmful gases. The experiment will assess the impact of different illumination durations, fixture heights, and brightness levels. Based on the findings, the number and arrangement of LED units will be optimized for maximum efficiency.

2.4. Evaluation of LED Anti-microbial Efficacy in Traditional Meat Stalls

LED fixtures will be tested for their ability to suppress pathogenic microorganisms. The experiment will be designed to assess the effects of varying illumination times, fixture heights, and brightness levels. These parameters will be used to determine optimal installation configurations for the LED units.

2.5. Evaluation of LED Efficacy in Degrading Airborne Particulate Matter in Traditional Meat Stalls

LED fixtures will be used to test their effectiveness in reducing airborne fine PM. The experimental design will evaluate the impact of different illumination durations, fixture heights, and brightness levels. The results will guide the configuration and number of LED fixtures to be installed.

2.6. Development of an AI-Based Monitoring System for LED-Controlled Decontamination in Traditional Meat Stalls

An artificial intelligence (AI)-based monitoring system will be developed to support the LED decontamination technology. The system will include sensors for detecting harmful substances and software capable of regulating the on/off status of LED fixtures in real-time, optimizing the efficacy of pollutant degradation and pathogen suppression.

2.7. Statistical Analysis

All values are presented as mean ± SD. One-way analysis of variance was conducted using Graphpad Prism 6 statistical software to analyze differences between different treatments. A significance level of $p < 0.05$ was considered statistically significant.

3. Results

3.1. Anti-microbial Efficacy

The anti-microbial efficacy test was conducted at 6 locations in Hsinchu City, Taiwan. The environmental bacterial counts before and after this new-generation LED light installation were measured (Figure 1). The results were presented that the significant anti-microbial efficacy were only found in field 1-3 after this new-generation LED were installed. Due to differing environmental conditions, the bacterial counts varied across locations before this new-generation LED installation. However, all sites showed a reduction in bacterial counts after this new-generation LED lights were installed (Figure 2).

Figure 1 The anti-microbial efficacy test was conducted at 6 locations in Hsinchu City, Taiwan. (A) Field 1; (B) Field 2; (C) Field 3; (D) Field 4; (E) Field 5; (F) Field 6

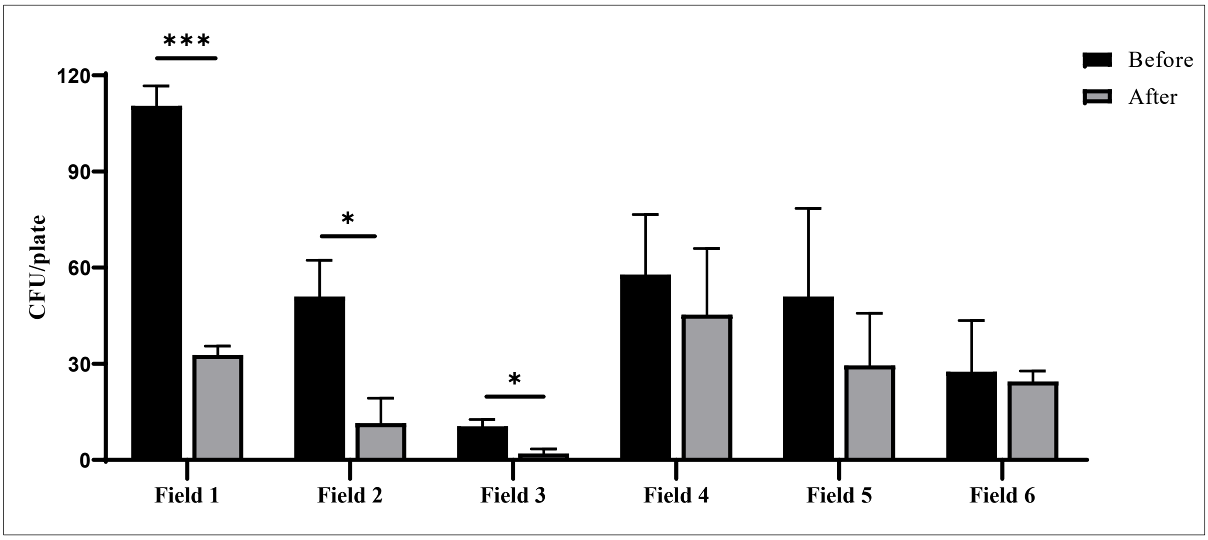

Figure 2 The anti-microbial efficacy test was conducted at 6 fields. The environmental bacterial counts before and after this new-generation LED light installation were measured. All values are presented as mean ± SD. A significance levels of $^{*}p < 0.05$ and $^{***}p < 0.001$ were considered statistically significant

3.2. Harmful Gas Decomposition Efficacy

As meat is exposed to air over time, microorganisms decompose the meat, releasing various malodorous and harmful gases. The concentrations of CH_4, NH_3, H_2S, and C_2H_4 were measured before and after this new-generation LED installation at each field. Notably, C_2H_4 concentrations significantly decreased after this new-generation LED installation at all sites ($p < 0.001$) (Figure 3). NH_3 was detected only at 2 fields before this new-generation LED installation. Its concentration also showed a significant decrease after installation ($p < 0.01$ to $p < 0.001$) (Figure 4). CH_4 and H_2S were not detected before or after this new-generation LED installation at any fields (data not shown).

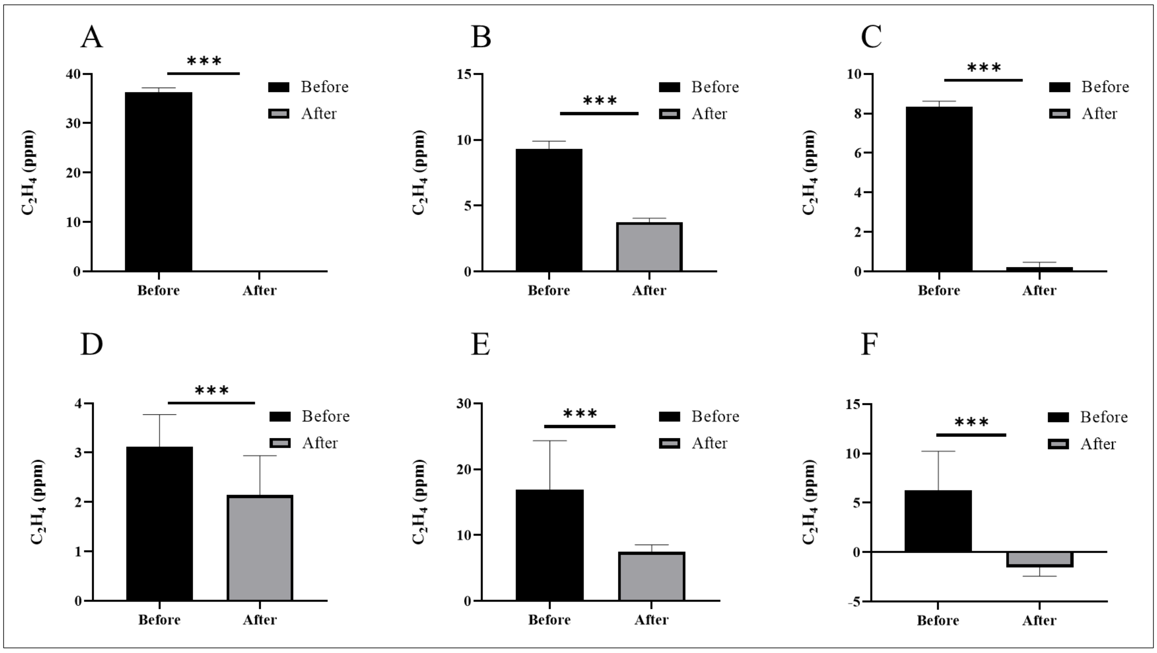

Figure 3 The C_2H_4 concentration was measured before and after this new-generation LED installation at each field. (A) Field 1; (B) Field 2; (C) Field 3; (D) Field 4; (E) Field 5; (F) Field 6. All values are presented as mean ± SD. A significance level of $^{***}p < 0.001$ was considered statistically significant

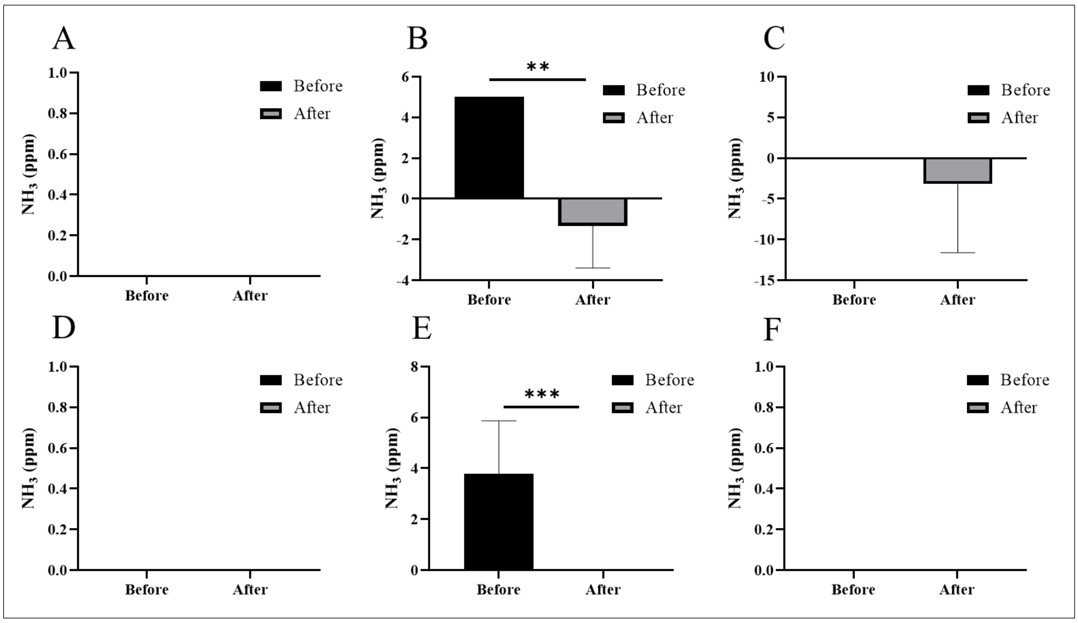

Figure 4 The NH_3 concentration was measured before and after this new-generation LED installation at each field. (A) Field 1; (B) Field 2; (C) Field 3; (D) Field 4; (E) Field 5; (F) Field 6. All values are presented as mean ± SD. A significance level of $^{**}p < 0.01$ and $^{***}p < 0.001$ were considered statistically significant

Formaldehyde (CH_2O) is one of the most common indoor air pollutants, found in over 3,000 types of construction materials such as fiberboard, plywood, sound insulation boards, and Styrofoam. It is irritating and can damage eyes and mucous membranes when its concentration in air exceeds 0.1 mg/m^3. CH_2O also exists naturally in small amounts in foods like vegetables, fruits, meats, and fish. However, it is water-soluble and can be removed from food through washing with tap water and cooking. CH_2O concentrations were measured before and after this new-generation LED installation at each field. The results showed a significant decrease in CH_2O levels after this new-generation LED installation ($p < 0.05$ to $p < 0.01$) (Figure 5).

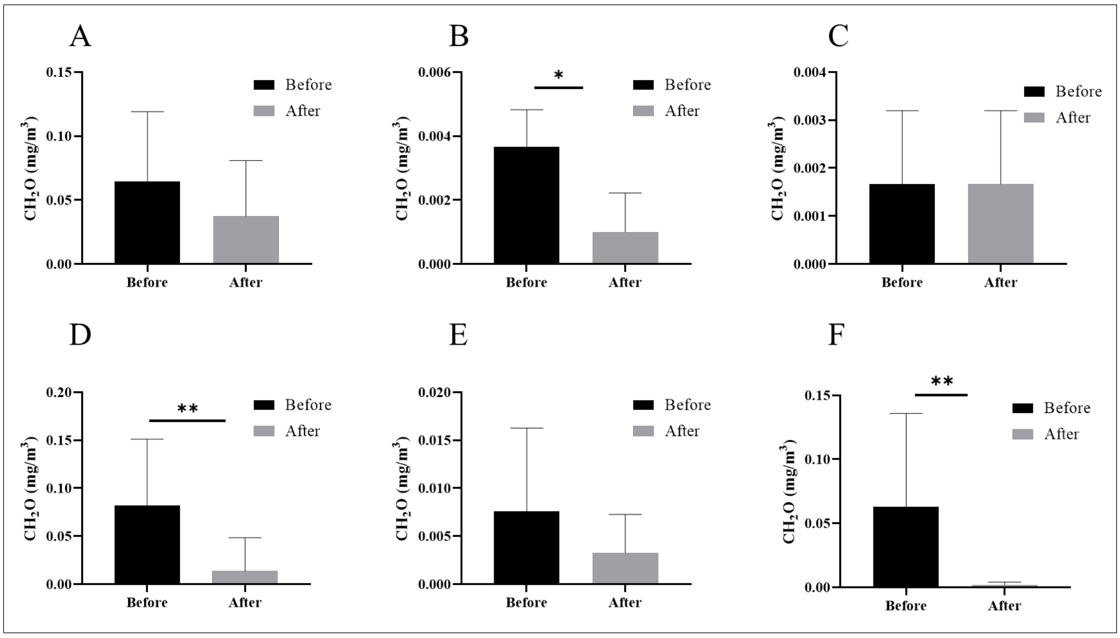

Figure 5 The CH_2O concentration was measured before and after this new-generation LED installation at each field. (A) Field 1; (B) Field 2; (C) Field 3; (D) Field 4; (E) Field 5; (F) Field 6. All values are presented as mean ± SD. A significance level of $^{*}p < 0.05$ and $^{**}p < 0.01$ was considered statistically significant

TVOC (total volatile organic compounds) refers to volatile organic substances existing as gases at room temperature, including benzene, carbon tetrachloride, chloroform, 1,2-dichlorobenzene, 1,4-dichlorobenzene, dichloromethane, ethylbenzene, styrene, tetrachloroethylene, trichloroethylene, toluene, and xylene. TVOCs can irritate the eyes and respiratory tract. Major environmental sources include fuel combustion and vehicle emissions, while indoor sources include paint, cooking, and smoking. TVOC concentrations were measured before and after this new-generation LED installation at each field. Results showed a significant reduction in TVOC levels after this new-generation LED installation at 4 fields ($p < 0.05$ to $p < 0.001$). However, a non-significant reduction of TOVC concentration before and after this new-generation LED installation at Field 3 was presented. Moreover, pre-installation TVOC level was already very low (0.0013 ± 0.0015 mg/m^3) at Field 6, so this new-generation LED's degradation effect was less noticeable at this field (Figure 6).

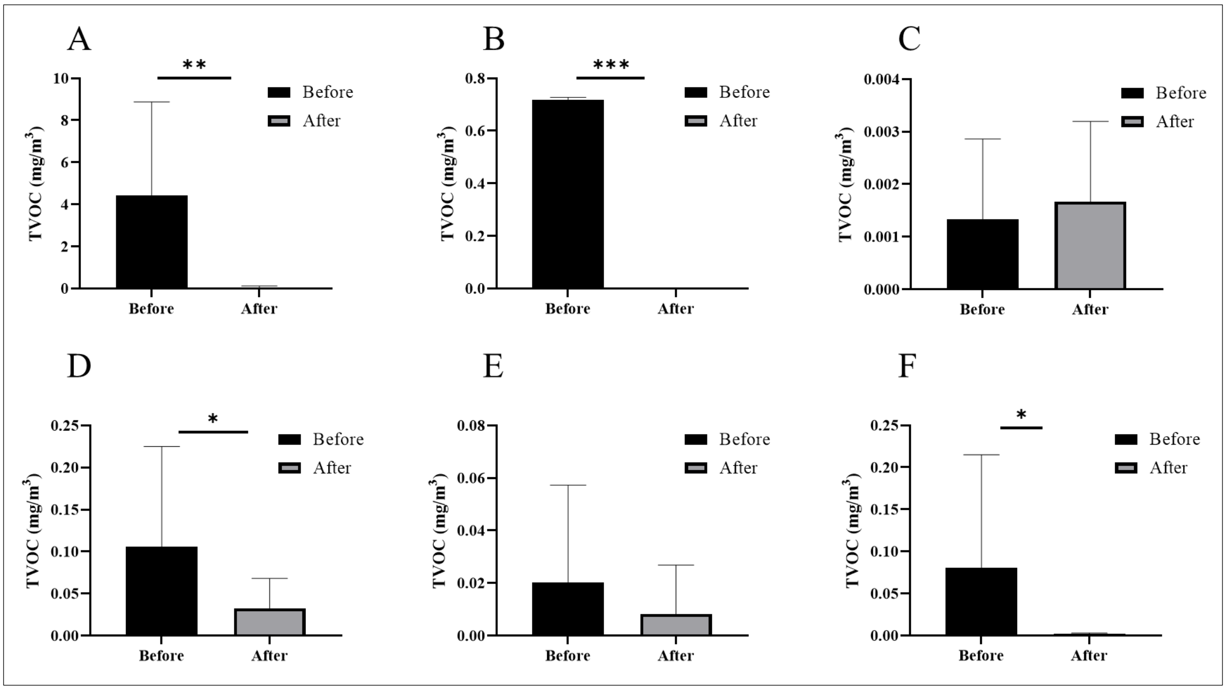

Figure 6 The TOVC concentration was measured before and after this new-generation LED installation at each field. (A) Field 1; (B) Field 2; (C) Field 3; (D) Field 4; (E) Field 5; (F) Field 6. All values are presented as mean ± SD. A significance level of $^{*}p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$ were considered statistically significant

3.3. Anti-microbial Efficacy

The anti-microbial effects before and after this new-generation LED installation were tested at each field. The new-generation LEDs were integrated with surface plasma structures to generate plasma waves, which ionize water molecules in the air. These ionized water molecules then contribute to the degradation and removal of airborne bacteria. The results showed anti-microbial rates ranging from 24.1% to 81.0% across the different fields (Figure 7).

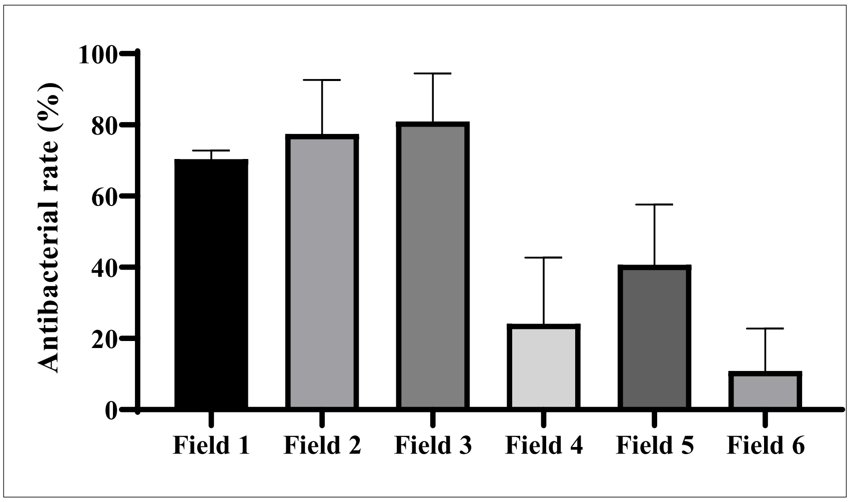

Figure 7 The anti-microbial effects before and after this new-generation LED installation were tested at each field. All values are presented as mean ± SD

3.4. Airborne Particulate Matter Decomposition

Particulate matter is classified by particle size: particles ≤ 2.5 micrometers (μm) are called $PM_{2.5}$, and those ≤ 10 μm are called PM_{10}. These particles can carry hazardous substances like dioxins, polycyclic aromatic hydrocarbons, and heavy metals. $PM_{2.5}$ is especially harmful as it can bypass the respiratory system's defenses and reach the lungs. Main sources include traffic emissions, industrial discharges, and animal farming. The concentrations of $PM_{2.5}$ and PM_{10} were measured before and after this new-generation LED installation at each field. At Field 1-3, both $PM_{2.5}$ and PM_{10} showed significant decreases after installation (Figures 8-9) ($p < 0.05$ to $p < 0.001$). Since cold storage areas are enclosed, they are less affected by external pollutants like traffic emissions, resulting in more noticeable $PM_{2.5}$ and PM_{10} reduction compared to other areas.

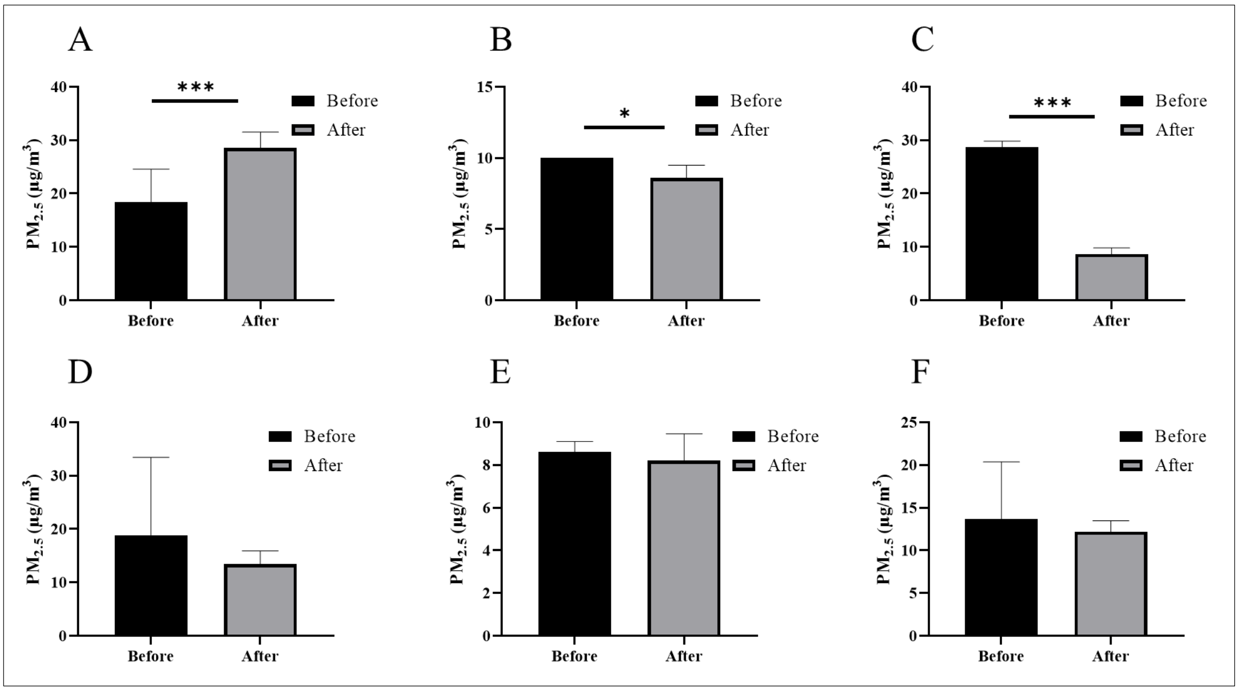

Figure 8 The airborne particulate matter 2.5 concentration was measured before and after this new-generation LED installation at each field. (A) Field 1; (B) Field 2; (C) Field 3; (D) Field 4; (E) Field 5; (F) Field 6. All values are presented as mean ± SD. A significance level of *$p < 0.05$ and ***$p < 0.001$ were considered statistically significant

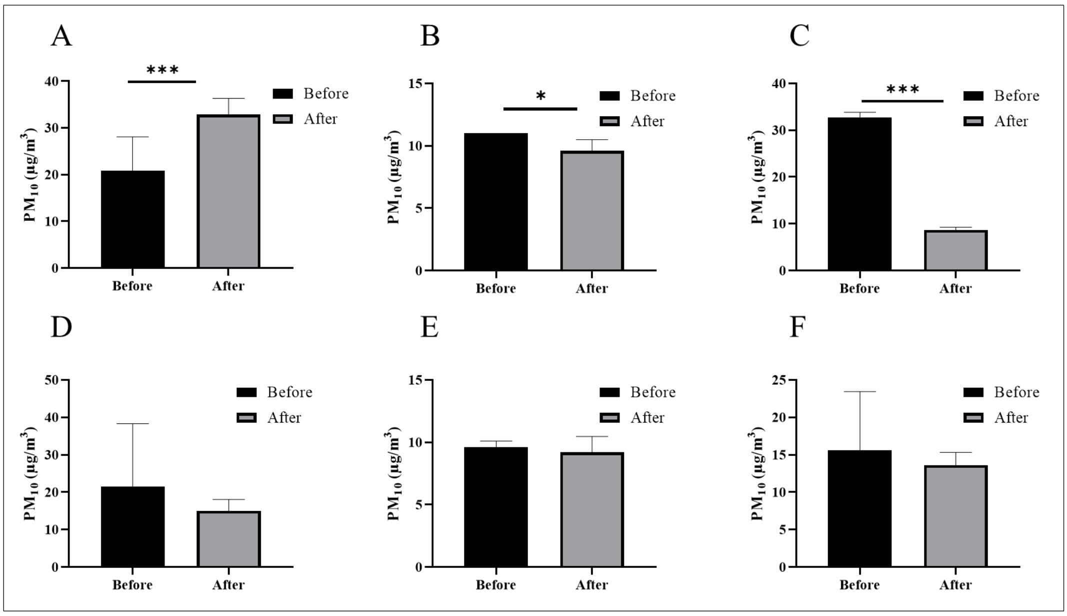

Figure 9 The airborne particulate matter 10 concentration was measured before and after this new-generation LED installation at each field. (A) Field 1; (B) Field 2; (C) Field 3; (D) Field 4; (E) Field 5; (F) Field 6. All values are presented as mean ± SD. A significance level of $^{*}p < 0.05$ and $^{***}p < 0.001$ were considered statistically significant

4. Discussion

SWOT (strengths, weaknesses, opportunities, and threats) analysis of the new-generation LED technology for biosafety applications and application focus at degradation of harmful substances in environmental control of traditional meat stalls and shops. For the strengths analysis, Taiwan holds a relative advantage over Southeast Asian countries and China in the monitoring of hazardous gases and pathogens, supported by its extensive experience in livestock and poultry farming. The nation's strong foundation in agricultural R&D and its alignment with forward-looking agri-tech innovations reflect national agricultural policies and sustainable development strategies. Moreover, the continuous and promising development of LED applications in agriculture offers new opportunities to strengthen food safety and agricultural resilience. For the weaknesses analysis, compared to leading nations, Taiwan's R&D capacity in related technologies still shows room for improvement. Research outcomes across ministries have not yet been systematically integrated or effectively promoted, limiting their overall impact. Furthermore, performance evaluation indicators and mechanisms for interdisciplinary technology projects are not sufficiently connected to real-world applications, highlighting the need for more application-driven strategies and implementation frameworks. For the opportunities analysis, with the rapid advancement of Taiwan's high-tech industry, there is significant potential for the application of LED technology in agriculture. The use of LEDs for the rapid degradation of harmful substances remains in its early stages both domestically and internationally, with no mature solutions currently available. Early investment and the establishment of an independent technological ecosystem would allow Taiwan to take a leading role in this emerging field, enhancing its global competitiveness. For the threats analysis, the developed countries such as those in Europe, the United States, and Japan have already established robust LED technology platforms and are gradually applying these technologies to the agricultural sector. Taiwan's relatively late entry into the field has resulted in a technological gap of several years. The development of critical core technologies also faces a shortage of skilled personnel. Meanwhile, other countries are ramping up R&D investments, intensifying global competition and potentially impeding Taiwan's progress in this domain [27-28].

According to our previous R&D results in lab's study, the experiments have shown that prototype LED lighting board can reduce harmful substances in pig farms. Prototype LED lighting board-white light exposure (8 or 16 hours) significantly reduced growth of *Pseudomonas aeruginosa* (PA) and *Staphylococcus aureus* (SA), with 8-hour exposure at 25 cm reducing PA by 89.1% and SA by 39.9%. Prototype LED lighting board-blue LED light at 15 cm had similar effects: PA reduced by 85.6% and SA by 40.7%. For ammonia gas degradation, 30-minute prototype LED lighting board exposure reduced levels by 35-45% (blue light) and 80% (white light). After 6 hours, prototype LED lighting board-white light reduced hydrogen sulfide by 50% and blue light by 29.4%. After 8 hours, reductions reached 68.8% (white light) and 52.9% (blue light). $PM_{2.5}$ concentrations dropped by nearly 80% after 100 minutes of exposure by prototype LED lighting board. Prototype LED lighting board-white light also showed clear antibacterial effects in field tests on pig farms, particularly after 4 hours. Preliminary trials on porcine reproductive and respiratory syndrome virus (PRRSV) found that one hour of prototype LED lighting board exposure significantly reduced viral titers in MARC 145 cells. In additional tests, prototype LED lighting board-white light effectively degraded harmful air pollutants including ammonia, hydrogen sulfide, formaldehyde, methane, $PM_{2.5}$, and PM_{10} when positioned at a height of 200 cm [17]. However, there is currently a lack of application in traditional meat stalls and retail environments. In this study, results demonstrated significant reductions in bacterial counts and concentrations of ethylene (C_2H_4) and ammonia (NH_3), while methane (CH_4) and hydrogen sulfide (H_2S) were undetectable before and after installation. Additionally, formaldehyde (CH_2O) and total volatile organic compounds (TVOCs) exhibited notable decreases. Antimicrobial efficacy rates ranged from 24.1% to 81.0% across different fields. In cold storage rooms, the levels of airborne particulate matter ($PM_{2.5}$ and PM_{10}) also significantly declined. Integrating this technology into traditional meat-selling venues could enable real-time degradation of airborne pathogens, harmful gases, and $PM_{2.5/10}$ during daily operations, contributing to the modernization of meat retail practices and advancing industrial development. In this study, these findings demonstrated that integrating advanced LED technologies in traditional meat retail environments can effectively reduce microbial and chemical hazards, enhance food safety, and support the modernization of the meat industry.

Previously, the application of this new-generation LED technology for the degradation of harmful substances have currently under development in various laboratory test domains. These include the use of this new-generation LED devices for anti-fungal activity, ethylene degradation, antibacterial and antiviral effects, $PM_{2.5}$ reduction, harmful gas (e.g., ammonia and hydrogen sulfide) degradation, anti-microbial computer screen development, and even potential anti-colorectal cancer effects. In anti-fungal and ethylene degradation tests, 450 nm wavelength new-generation LED devices showed a time-dependent reduction in ethylene concentration after 30-240 minutes of illumination [16-17, 24-26]. The degradation rate of ethylene reached approximately 20% after 30 minutes and over 40% after 240 minutes [16-17, 24-26]. Additionally, the anti-fungal effects were evaluated using mold growth on apple cross-sections. Results demonstrated a significant reduction in mold area under this new-generation LED devices compared to the conventional LED devices after 4-7 days of exposure [16-17, 24-26]. Anti-microbial efficacy was assessed by measuring airborne bacterial concentrations and inhibition of bacterial growth on agar plates. The 450 nm new-generation LED devices significantly reduced airborne bacterial counts and more effectively suppressed the growth of eight *Salmonella* strains compared to the conventional LED devices [16-17, 24-26]. For anti-viral testing, the effect of this new-generation LED devices on porcine reproductive and respiratory syndrome virus (PRRSV) was evaluated by measuring C_t values. The 450 nm new-generation LED devices significantly lowered C_t values, indicating a stronger anti-viral effect compared to the conventional LED devices [16-17, 24-26]. Regarding $PM_{2.5}$ reduction, 450 nm new-generation LED devices showed a time-dependent decrease in $PM_{2.5}$ concentration in laboratory settings [17, 24-26]. A similar effect was observed in pig farms after 6 hours of exposure [17, 24-26]. For harmful gas degradation, this new-generation LED devices significantly reduced NH_3 and H_2S concentrations in pig farm environments after 4-5 hours of exposure, with a clear time-dependent trend [17, 24-26]. Taken together, these previous and current findings demonstrate this new-generation LED technology can be used in the biosafety applications as application of the new-generation LED technology for degradation of harmful substances in environmental control of traditional meat stalls and meat shops.

5. Conclusion

In this study, the new-generation LED installation significantly reduced environmental bacterial counts. They also markedly lowered concentrations of ethylene (C_2H_4) and ammonia (NH_3). Methane (CH_4) and hydrogen sulfide (H_2S) were not detectable at any site, either before or after installation. Additionally, formaldehyde (CH_2O) and total volatile organic compound (TVOC) levels showed significant reductions or downward trends following the installation of the new-generation LED. In the antimicrobial efficacy tests, the reduction rates ranged from 24.1% to 81.0% across various test sites. Furthermore, in airborne particulate matter decomposition tests, $PM_{2.5}$ and PM_{10} concentrations were significantly decreased in cold storage rooms after the new-generation LED installation.

Compliance with ethical standards

Acknowledgments

All authors thank Ministry of Agriculture [grant number 111AS-2.1.1-AD-U3 and 112AS-2.1.5-AD-U1, 113AS-2.1.4-AD-01), 114AS-2.1.3-AD-01], National Science and Technology Council [NSTC 111-2622-B-866-003], Hong Zhao Co., LTD. [grant number AAI-01-E-C11110], and Thunder Soul Co., LTD. [grant number AAI-02-E-C11110] for supporting this study.

Disclosure of conflict of interest

The authors declare no conflict of interest.

References

[1] Luksiene Z, Brovko L. 2013. Antibacterial photosensitization-based treatment for food safety. Food Eng Rev. 5: 185-199.

[2] Kim MJ, Mikš-Krajnik M, Kumar A, Yuk HG. 2016. Inactivation by 405 ± 5 nm light emitting diode on Escherichia coli O157: H7, Salmonella typhimurium, and Shigella sonnei under refrigerated condition might be due to the loss of membrane integrity. Food Control. 59: 99-107.

[3] Kim MJ, Bang WS, Yuk HG. 2017. 405 ± 5 nm light emitting diode illumination causes photodynamic inactivation of Salmonella spp. on fresh-cut papaya without deterioration. Food Microbiol. 62: 124-132.

[4] Brovko LY, Meyer A, Tiwana AS, Chen W, Liu H, Filipe CD, Griffiths MW. 2009. Photodynamic treatment: a novel method for sanitization of food handling and food processing surfaces. J Food Prot. 72: 1020-1024.

[5] Ghate V, Ng KS, Zhou W, Yang H, Khoo GH, Yoon WB, Yuk HG. 2013. Antibacterial effect of light emitting diodes of visible wavelengths on selected foodborne pathogens at different illumination temperatures. Int J Food Microbiol. 166: 399-406.

[6] Dai T, Gupta A, Huang YY, Yin R, Murray CK, Vrahas MS, Sherwood ME, Tegos GP, Hamblin MR. 2013. Blue light rescues mice from potentially fatal Pseudomonas aeruginosa burn infection: efficacy, safety, and mechanism of action. Antimicrob Agents Chemother. 57: 1238-1245.

[7] McDonald RS, Gupta S, Maclean M, Ramakrishnan P, Anderson JG, MacGregor SJ, Meek RM, Grant MH. 2013. 405 nm light exposure of osteoblasts and inactivation of bacterial isolates from arthroplasty patients: potential for new disinfection applications? Eur Cell Mater. 25: 204-214.

[8] Guffey JS, Wilborn J. 2006. Effects of combined 405-nm and 880-nm light on Staphylococcus aureus and Pseudomonas aeruginosa in vitro. Photomed Laser Surg. 24: 680-683.

[9] Luksienė Z, Kokstaite R, Katauskis P, Skakauskas V. 2013. Novel approach to effective and uniform inactivation of Gram-positive Listeria monocytogenes and Gram-negative Salmonella enterica by photosensitization. Food Technol Biotech. 51: 338-344.

[10] Kumar A, Ghate V, Kim MJ, Zhou W, Khoo GH, Yuk HG. 2016. Antibacterial efficacy of 405, 460 and 520 nm light emitting diodes on Lactobacillus plantarum, Staphylococcus aureus and Vibrio parahaemolyticus. J Appl Microbiol. 120: 49-56.

[11] Kumar A, Ghate V, Kim MJ, Zhou W, Khoo GH, Yuk HG. 2015. Kinetics of bacterial inactivation by 405 nm and 520 nm light emitting diodes and the role of endogenous coproporphyrin on bacterial susceptibility. J Photochem Photobiol B. 149: 37-44.

[12] De Lucca AJ, Carter-Wientjes C, Williams KA, Bhatnagar D. 2012. Blue light (470 nm) effectively inhibits bacterial and fungal growth. Lett Appl Microbiol. 55: 460-466.

[13] Gillespie JB, Maclean M, Given MJ, Wilson MP, Judd MD, Timoshkin IV, MacGregor SJ. 2017. Efficacy of pulsed 405-nm light-emitting diodes for antimicrobial photodynamic inactivation: effects of intensity, frequency, and duty cycle. Photomed Laser Surg. 35: 150-156.

[14] Ramakrishnan P, Maclean M, MacGregor SJ, Anderson JG, Grant MH. 2016. Cytotoxic responses to 405 nm light exposure in mammalian and bacterial cells: involvement of reactive oxygen species. Toxicol In Vitro. 23: 54-62.

[15] Maclean M, MacGregor SJ, Anderson JG, Woolsey G. 2009. Inactivation of bacterial pathogens following exposure to light from a 405-nanometer light-emitting diode array. Appl Environ Microbiol. 75: 1932-1937.

[16] Chen CC, Chi TY, Li CL, Hung YC, Chen HY, WD, Lin CY, Lai SQ, Tsung CS, Chiu CC, Lin JS, Huang PM, Wu TH, Chen YH, Lin PH, Hsu SF, Hung SW. 2020. Application and development of triple functional features of the novel light-emitting diode module in pig farms. Unite J Vet Sci Technol. 1: 1-4.

[17] Hung YW, Chi TY, Lai SQ, Wang YP, Cyue YL, Chen PH, Lu YJ, Guo SY, Fang YY, Wu YZ, Chiu CC, Chiu CF, Chiu HW, Lin YH, Hsu CY, Fang WD, Wu TH, Hung SW. 2023. Application of degradation technology of light-emitting diode and auto-monitoring system for harmful substances in farrowing areas of a specific pathogen-free pig farm. Int J Sci Res Updates. 6: 59-66.

[18] Zhu J, Chen L, Liao H, Dang R. 2019. Correlations between PM2.5 and Ozone over China and associated underlying reasons. Atmosphere. 10: 352.

[19] Mihina S, Sauter M, Palkovičová Z, Karandušovská I , Brouček J. 2012. Concentration of harmful gases in poultry and pig houses. Anim Sci Pap Rep. 30: 395-406.

[20] Dee S, Guzman JE, Hanson D, Garbes N, Morrison R, Amodie D, Galina Pantoja L. 2018. A randomized controlled trial to evaluate performance of pigs raised in antibiotic-free or conventional production systems following challenge with porcine reproductive and respiratory syndrome virus. PLoS One. 13: e0208430.

[21] Hung YW, Tsung CS, Lin YH, Chiu CF, Chiu CC, Chiu HW, Tsai WH, Hung SW. 2019. Study of phototoxicity of LED light for colon cancer. Biomed J Sci Tech Res. 13: 10167-10169.

[22] Hung YW, Tsung CS, Lin YH, Chiu CF, Chiu CC, Chiu HW, Tsai WH, Hung SW. 2019. Study of phototoxicity of LED light for colon cancer. Biomed J Sci Technol Res. 13(4): 10167-10169. DOI: 10.26717/BJSTR.2019.13.002443.

[23] Sparsa A, Faucher K, Sol V, Durox H, Boulinguez S, Doffoel-Hantz V, Calliste CA, Cook-Moreau J, Krausz P, Sturtz FG, Bedane C, Jauberteau-Marchan MO, Ratinaud MH, Bonnetblanc JM. 2010. Blue light is phototoxic for B16F10 murine melanoma and bovine endothelial cell lines by direct cytocidal effect. Anticancer Res. 30: 143-148.

[24] Chi TY, Li CL, Tsung CS, Chen CC, Hung YC, Lin CY, Hung YW, Chiu CF, Chiu CC, Chiu HW, Lin YH, Tsai WH, Lin JS, Hung SW. 2019. Research and development of dual functional features of light-emitting diode: degradation of atmospheric fine particulate matter and antimicrobial efficacy. Biomed J Sci Tech Res. 20: 15273-15277.

[25] Chi TY, Li CL, Tsung CS, Chen CC, Hung YC, Lin CY, Hung YW, Chiu CF, Chiu CC, Chiu HW, Lin YH, Tsai WH, Lin JS, Hung SW. 2019. Research and Development of Dual Functional Features of Light-emitting Diode: Degradation of Atmospheric Fine Particulate Matter and Antimicrobial Efficacy. Biomed J Sci Tech Res. 20(4). DOI: 10.26717/BJSTR.2019.20.003491.

[26] Lin YH, Chi TY, Chang YX, Lin CY, Wang YP, Chen HY, Huang PM, Chen GH, Hung YC, Wu TH, Lu YJ, Chiu CC, Chiu CF, Chiu HW, Tsai WH, Chen CC, Hung SW. 2022. Application of the novel environment-cleaned light-emitting diode devices in various test fields. World J Adv Sci Technol. 1(2): 20-32.

[27] Luksiene Z. 2009. Photosensitization for food safety. Chemine Technologija. 4: 62-65.

[28] Jia M, Zhao T, Cheng X, Gong S, Zhang X, Tang L, Liu D, Wu X, Wang L, Chen Y. 2007. Inverse relations of PM2.5 and O3 in air compound pollution between cold and hot seasons over an urban area of East China. Atmosphere. 8: 59.